NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

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EFFECT OF VARIABLES IN WELDING TECHNIQUE ON THE STRENGTH OF DIRECT-CURRENT METAL-ARC-WELDED JOINTS IN AIRCRAFT STEEL

I - STATIC TENSION AND BENDING FATIGUE TESTS OF JOINTS IN SAE 4130 STEEL SHEET

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SUMMARY

Arc-welded butt joints in 1/8-inch SAE 4130 steel sheet of aircraft quality, which were made under various conditions of welding and heat treatment, were tested to evaluate the effects of specific welding-technique factors on the strength of the joints. The results of the tensile tests indicated that crater blowholes, or crater cracks, produced by interrupting the weld, had the most pronounced influence on the transverse tensile strength of the butt-welded specimens; that position of welding had no significant effect on the tensile strength of any group of specimens; that preheating produced no increase in either the soundness or strength of the welds; and that welds made with alloy-steel electrodes were stronger than those made with plain-carbon-steel electrodes. It was found that the factor having the greatest influence on the plate-bending fatigue strength of the welded specimens was the external stress-raiser at the toe of welds in the reinforced specimens.

INTRODUCTION

The increasing use of metal-arc welding in the fabrication of steel aircraft structures, brought about by the desire for increased production and other advantages inherent in the metal-arc-welding method, has also brought into focus certain of its limitations. The level of weldability of aircraft steels, for example, is a very important factor, and the suitability of various types of electrodes for aircraft welding has been extensively investigated. The development of proper welding techniques has also been given much attention, since experience has shown that many of the difficulties in the fabrication of welded airframes, such as distortion, cracking, and certain types of weld defects, may have their origin in faulty welding technique.

The influence of weld penetration, contour, craters, undercutting, and similar factors on the structural integrity of aircraft joints is recognized, but the degrees in which these factors affect the static and dynamic strength are not yet fully understood. This investigation was originally set up to study the effect of those factors and several others, such as hardness, grain size, and chemical-composition gradients, on the strength of joints in SAE 4130 aircraft steel welded by the direct-current metal-arc method. These factors are influenced by the skill of the welding operator, type and size of electrode, welding current, speed and position of welding preheat, heat treatment after welding, and the size, geometry, degree of restraint, and surface conditions at the weld joint.

The investigation reported herein was conducted under the sponsorship and with the financial assistance of the National Advisory Committee for Aeronautics.

MATERIALS AND EQUIPMENT

Steel.- All metal-arc-welded specimens for the static tension and bending fatigue tests described in this report were made from aircraft-quality SAE 4130 steel sheet, 1/8-inch thick. The chemical composition and strength of the material are given in table 1.

Welding electrodes.- The electrodes used in the welding of the test specimens were a plain-carbon-steel electrode and an aircraft welding electrode which produces an alloy-steel weld metal. It was specified, on the basis of a questionnaire sent to aircraft factories, that Wilson No. 520 and Lincoln Planeweld No. 1 electrodes be used.

Welding machine.- It was further specified that a direct-current motor-generator welding machine, of the type designed for airframe welding, be used. The use of crater-eliminating devices (remote current control) was not desired.

STATIC TENSION TESTS OF METAL-ARC-WELDED SAE 4130 STEEL SHEET

Preparation of Specimens

Welded tension specimens were prepared in 1/8-inch SAE 4130 sheet as shown in figure 1 with welding conditions as given in table 2. For each combination of welding conditions (electrode, preheat, position, and heat treatment after welding), eight tension specimens were made. Four of these specimens had a weld made in a continuous bead with the arc break, when required, outside the boundaries of the tension coupon. The four other specimens were made with discontinuous welds; that is, the weld was stopped, the crater cleaned in the usual manner, and welding resumed at definite points along the length of the weld groove. The tension specimens were then cut to include the interrupted portions of the welds.

The welds were made manually in a single bead from one side only, with current and speed adjusted to obtain the maximum root fusion possible without the specimen melting through. Neither metallic nor refractory strips were used to back up the weld groove. The single-bead weld was used, rather than a joint welded from both sides, because (a) the one-side butt weld is often encountered in aircraft work and is more sensitive to internal defects, (b) it was desired to test a weld with no secondary heat effects resulting from a root or reinforcing pass, and (c) the second pass would have eliminated incomplete fusion at the root, which was also to be studied.

The face of the single-bead weld and irregularities on the root side were ground approximately flush with the surface of the sheet, but no attempt was made to remove undercutting or to obtain a perfectly flush or smooth surface.

The amperage and arc voltage reported in table 1, as well as in succeeding tables of welding data, were measured as accurately as possible with sensitive meters. Preheat temperatures were measured to ±10° F. Welding speeds (arc time) were measured with a stop watch. All stress-relief and heat treatments of SAE 4130 steel specimens (including butt-welded sheet and fillet-welded tube-plate specimens, reference 1) were done in a salt bath, except that drawing of quenched specimens was done in an electric muffle furnace.

Radiographs of Weld Joints

After machining, all specimens were X-rayed to locate the interrupted-weld areas and other defects. Prints of these X-rays are shown in figures 2 to 17, with the ultimate tensile strength of each specimen and the welding conditions used for each group of eight specimens.

Although the four specimens at the left of each radiograph had continuous welds and were meant to be as sound and fully welded as possible, there were numerous instances in which these welds had pronounced defects, principally lack of fusion at the root. With one or two exceptions, however, the presence of these defects in the continuous welds did not seriously reduce the static tensile strength.

In the four specimens at the right in each radiograph, the number of weld defects was considerably greater, and there were distinct indications of crater blowholes, transverse crater cracking, and incomplete fusion at the start of the second pass. These defects in the interrupted welds had an appreciable effect on the static tensile strength. The presence of a flaw in the interrupted weld did not in every case cause a reduction in strength, but if the results are analyzed by groups, it becomes evident that the continuous welds were stronger than the interrupted welds, even though the radiographs in some cases indicate that one group was no better than the other.

Static Tension Tests

The ultimate tensile strength for each specimen is shown in the radiographs, and the average strength for each group of four specimens is given in table 3A. These data show clearly that the effect of weld interruptions is to reduce the static tensile strength of the immediate weld area. It is interesting to note that the position of welding had little effect on the strength of the joints; indeed, in this series of tests the average strength of the overhead welds was slightly greater than the strength of the flat and vertical welds. Preheat, likewise, had no discernible effect on the strength of the welded joints. This might not be the case, however, for joints in material thicker than 1/8 inch.

The effects of heat treatment after welding are also given in table 3A. The welds made with plain-carbon-steel electrodes gained about 30 percent in tensile strength, for both continuous and interrupted welds, as a result of the heat treatment used. The welds made with alloy-steel electrodes gained 40 percent (interrupted welds) to 50 percent (continuous welds) in strength after heat treatment.

A summary of the static-tension-test data is given in table 3B and shows the decrease in tensile strength caused by interruptions in the weld.

An analysis of the location of tension fractures is given in table 3C with significant points as follows:

1. All heat-treated specimens made with carbon-steel electrodes failed in the weld.

2. All heat-treated interrupted-bead specimens made with alloy-steel electrodes failed in the weld.

3. Most of the heat-treated continuous-bead specimens made with alloy-steel electrodes failed in the weld.

4. All as-welded interrupted-bead specimens made with carbon-steel electrodes failed in the weld.

5. Over one-third of the as-welded continuous-bead specimens made with carbon-steel electrodes had weld joints stronger than the parent plate.

6. Three-fourths of the as-welded interrupted-bead specimens made with alloy-steel electrodes failed in the weld.

7. Only one-fourth of the as-welded continuous-bead specimens made with alloy-steel electrodes failed in the weld.

FATIGUE TESTS OF METAL-ARC-WELDED SAE 4130 STEEL SHEET

Preparation of Specimens

Metal-arc-welded fatigue-test specimens were made from 1/8-inch SAE 4130 steel sheet as shown in figures 18 and 19 with welding conditions described in table 4. Normalized plates were used for all specimens, but no heat treatment after welding was used.

The butt joint was a 90° closed single groove. (See fig. 18.) The weld was made either with two beads (root and face), or with a single-face bead, by using plain-carbon-steel welding electrodes. Some specimens in each set were made with continuous manual welds across the entire width of the plate, and others were made with interrupted welds to produce a crater at the center of the specimen. (See groups 3, 4, 7, and 8, fig. 18.) After the first half of the interrupted face bead was completed, the crater was wire-brushed but otherwise not disturbed. The remaining half of the bead was then welded with sufficient pause at the crater to permit good penetration in that area. No attempt was made, however, to fuse completely the crater cracks or blowholes.

The plates were preheated to 300° F before welding in order to obtain easy starting conditions and uniform penetration for the entire length of the weld. In the two-bead specimens the root weld was made first, so that the face weld could be deposited more easily with higher heat input and maximum penetration without danger of melting through the feather edge of the scarfed joint. The welding current, arc voltage, and welding time were measured with automatic recording equipment and are given in table 4.

The welded specimens were then milled with the aid of a templet and jig to the contour shown in figure 19. This taper contour provided for a constant fiber stress in the region of the weld when the specimens were tested in bending fatigue as cantilever beams. After contour milling, half of the specimens were ground on both sides to a smooth surface with no weld reinforcement (groups 2, 4, 6, and 8, fig. 18). The remaining specimens were left with the natural weld reinforcements (groups 1, 3, 5, and 7, fig. 18).

Radiographs of Weld Joints

Prior to fatigue testing, all welded specimens were X-rayed to bring out internal defects at the welds. The radiographs are shown in figures 21 to 28. The location of fatigue failure is indicated in the radiographs by horizontal arrows and is discussed in the succeeding sections.

Fatigue Tests

The plate-bending fatigue tests were carried out on a 100-pound capacity Krouse plate-bending machine with a maximum deflection of ±1 inch. The specimens were gripped at the wide taper end, and the load was applied at the narrow taper end through a crank arm, the throw of which could be adjusted by means of an eccentric rotor. A typical specimen ready for testing is shown in figure 20.

In order to obtain the maximum fiber stress in the reduced section of the test specimen, several representative specimens were first calibrated by measuring the deflection at the load end for several increments of dead-weight loading. The stress for a given deflection was computed from the cantilever-beam formula, and the testing machine was then adjusted for deflections to produce the desired stress in the region of the weld.

In order to check this method, a representative surface-ground specimen was equipped with electrical-resistance strain gages on both surfaces, spanning the weld zone, and the stresses at various deflections were measured. It was found that the stresses measured by the strain-gage method checked within 5 percent of the stresses computed by the load-deflection method.

The several groups of specimens were loaded at various stress levels (see table 5) and the test was carried to failure, or to not less than about 5 million cycles of completely reversed bending stress. All specimens were tested in the as-welded condition. The fatigue strength of the specimens is given in table 5, and the data are graphed in figures 29 and 30. These figures also show reference S-N curves, taken from another investigation on 1/8-inch SAE 4130 steel with the same mechanical and chemical properties, for unwelded specimens with no surface treatment and with the surfaces ground smooth.

Results of tests on two-bead weld specimens.- Figure 29 shows the fatigue strength of specimens with face and root beads, with continuous and interrupted welds, and with full reinforcement and a surface-ground weld. The specimens with two-bead, continuous, surface-ground welds (group 2) had the highest fatigue strength, which was appreciably higher than that of the unwelded control specimens with no surface treatment (line B), but below that of surface-ground unwelded plate (line A). The fatigue strength of group 2 was probably influenced by the lower strength of the weld metal (two specimens failed on the weld and two in the fusion line), although no internal weld effects were discernible in the radiographs (figs. 22(a) and 22(b)).

The varied location of the group 2 fatigue fractures also indicated that the decrease in fatigue strength from the line A level could not be attributed solely to welding effects. It is believed that the surface decarburization remaining in the specimens (the surfaces of which were not machined so deep as the line A specimens) contributed to the decrease in fatigue strength. It is also significant that the group 2 specimens, which had only a few thousandths of an inch removed from the surface, were stronger in fatigue than the line B unwelded specimens which had no surface treatment.

Continuous two-bead weld specimens with full reinforcement (group 1) had a much lower fatigue strength than similar surface-ground specimens (group 2). In all cases the specimens in group 2 failed at the toe of the larger (face) bead and thus indicated the pronounced effect of the stress concentration at that point. (See radiographs, figs. 21(a) and 21(b).)

The interrupted-weld specimens with full reinforcement (group 3) also failed at the toe of the face bead. (See radiographs, figs. 23(a) and 23(b).) Probably there were internal defects at the point of interruption of the weld, but they are not visible in the radiographs and, if present, had no chance to influence the fatigue strength because of the greater influence of the external stress-raiser at the toe of the face bead. Figure 29 shows that the toe-of-weld stress-concentration effect was greater for the interrupted-weld specimens (group 3) than for the continuous-weld specimens (group 1). This is possible because the face bead in the group 3 specimens was higher and fuller with incipient overlapping at the weld interruption.

The surface-ground, interrupted, two-bead welds (group 4) had a higher fatigue strength than the companion specimens with full reinforcement (group 3). The radiographs in figures 24(a) and 24(b) indicate that the location of fatigue failure of the group 4 specimens was influenced by the presence of crater defects at the weld interruption, although the fatigue strength of weld metal itself may have had an effect.

It is significant that the internal defects in the specimens of group 4 had a less deleterious effect on the plate-bending fatigue strength than the external toe-of-weld stress-raisers (which might well be called defects as far as fatigue strength is concerned) in the companion group 3 specimens. In bending, the surface of the specimens is more highly stressed than the internal fibers. In axial loading the stress is nearly uniform across the section, and internal defects of the magnitude shown in figures 24(a) and 24(b) would no doubt exert a greater influence on fatigue strength.

Results of tests on single-bead weld specimens.- Figure 30 presents the fatigue data on specimens with continuous and interrupted single-bead welds with and without weld reinforcement. There is no significant difference in the fatigue behavior of the various types of welds (groups 5, 6, 7, and 8) so far as the S-N data are concerned. The only group which departed appreciably from the base line B for unwelded specimens is group 8, in which large crater blowholes were present at the weld interruption. (See radiographs, fig. 28.)

The continuous single-bead surface-ground specimens (group 6) failed outside the weld zone at the end of the tapered section because of the secondary stress concentration at the change of section at the grip. (See fig. 26.) The two sets of specimens with reinforcement intact (groups 5 and 7) failed at the toe of the weld. Group 7 had internal crater defects of considerable size (see fig. 27, particularly specimen 586-7), but these had no effect on the fatigue strength.

Typical fatigue fractures.- Figures 31, 32, and 33 show typical plate-bending fatigue fractures for the various types of weld specimens.

DISCUSSION OF RESULTS

Static Tension Tests

The most pronounced influence on the transverse tensile strength of the butt-welded specimens appeared to be that of the crater blowholes or crater cracks, which were produced by interrupting the weld. In most cases this condition caused a decrease in the strength from that of companion continuous-weld specimens which had no crater defects.

Some of the continuous-weld specimens had other weld defects (lack of complete penetration to the root of the weld), but these had less effect on the transverse tensile strength than the crater defects in interrupted-weld specimens.

The position of welding had no significant effect on the tensile strength of any group of specimens, other conditions being equal.

Preheating of the plates to 300° F produced no increase in either the soundness or strength of the welds. This does not mean that preheat is unnecessary in metal-arc welding of the aircraft structural steels. It is often desirable to use preheat to prevent cracking of the steel adjacent to the weld. The present indications are, however, that preheating is of doubtful value as a means of improving the quality of welds (absence of crater or root defects) in thin plates.

The welds made with alloy-steel electrodes were stronger than those made with plain-carbon-steel electrodes. The degree and character of weld defects were comparable for both types of electrodes, but the added strength of the alloy-steel welds helped to nullify the effect of weld defects. The alloy-steel welds also showed a greater increase in strength when heat treated after welding.

It is to be noted that all these data are for single-bead welds with the face reinforcement removed. If the weld reinforcement had not been removed, the increased cross section at the weld undoubtedly would have caused more failures in the parent plate or at the fusion zone at higher strengths. In such welds the effect of internal defects would be less pronounced than when the reinforcement is removed.

Fatigue Tests

In the eight types of weld-joints tests (see fig. 18), there were two principal differences:

1. The joints either had the natural weld reinforcement or were machined flush with the surface of the plates.

2. The joints either had a sound weld (continuous bead) or a weld with internal crater defects (interrupted bead).

The factor which had the greatest influence on the plate-bending fatigue strength of the welded specimens was the external stress-raiser at the toe of welds in the reinforced specimens. The internal stress-raisers, caused by crater blowholes or cracks, caused failure only when the weld reinforcement (and hence the external stress-raiser) was removed. The probable explanation for this was that in the plate-bending test, the surface had a higher stress than the internal fibers. If a uniformly distributed stress were used (axial tension fatigue) the influence of internal defects would be more pronounced. However, the effect of external stress-raisers at the toe of reinforced welds would still be critical.

No specimens were tested in this series which were heat treated after welding. Results of tests on other plates of welded specimens (reference 1) indicate that while the fatigue strength may improve if the tensile strength is increased by heat treatment, the effect of stress concentrations arising from geometry of the joint is very great and all but vitiates any improvement derived from heat treatment.

The present tests show some evidence that surface decarburization exerts a marked influence on fatigue strength. This is indicated by the tests of surface-ground specimens and as-rolled specimens (see fig. 29), but the test data for the metal-arc-welded specimens are insufficient for conclusion. However, the results of other investigations of the fatigue strength of SAE 4130 steel show quite conclusively that decarburization may be an important factor. This has little to do with welding technique, but is mentioned here because most of the commercially supplied aircraft steel of the 4130 type is decarburized to some degree at the surface. Since the most critical stress concentrations in welded aircraft steel parts are often at the surface, adjacent to welds, the added influence of the decarburized layer with its lower inherent fatigue strength should not be overlooked in a consideration of fatigue behavior.

Battelle Memorial Institute,
Columbus, Ohio, May 1944.

REFERENCE

1. Voldrich, C. B., Armstrong, E. T., and Jackson, L. R.: Effect of Variables in Welding Technique on the Strength of Direct-Current Metal-Arc-Welded Joints in Aircraft Steel. II - Repeated Stress Tests of Joints in SAE 4130 Seamless Steel Tubing. NACA TN No. 1262, 1947.

TABLE 1. PROPERTIES OF 1/8-INCH SAE 4130 STEEL SHEET (1) USED FOR METAL-ARC BUTT WELD TENSION AND FATIGUE TEST SPECIMENS

Chemical Composition, Per Cent (Mill Analysis)						
C	Mn	P	S	Si	Cr	Mo
0.31	0.47	0.023	0.017	0.25	0.94	0.21
.32	.47	.023	.020	.26	.95	.23

Mechanical Properties			
Yield Strength, p.s.i.	Ultimate Tensile Strength, p.s.i.	Elongation, % in 2"	Rockwell B Hardness
81,400	97,500	22	92

(1) Hot-rolled; normalized and drawn to strength shown.

TABLE 2. WELDING DATA FOR SINGLE-BEAD BUTT WELDS IN 1/8-INCH SAE 4130 SHEET FOR STATIC TENSION TEST

Test No.	Electrode Used		Initial Plate Temp. °F.	Welding Position	Direct Current, Electrode Negative		Welding Speed, In./Min. (1)	Heat Treatment After Welding	Radiograph Shown in Figure:
	Kind	Core Diam., Inches			Amperes	Arc Volts			
419	Wilson 520 (2)	1/8	70	Flat	110-115	19-21	7	None	2
420	Ditto	1/8	300	Flat	105-110	20-22	8	"	3
421	"	3/32	70	Vert. (up)	70-75	21-23	6	"	4
422	"	1/8	70	O'head	105-110	19-21	-	"	5
419	"	1/8	70	Flat	110-115	19-21	7	QD(4)	6
420	"	1/8	300	Flat	105-110	20-22	8	"	7
421	"	3/32	70	Vert. (up)	70-75	21-23	6	"	8
422	"	1/8	70	O'head	105-110	19-21	-	"	9
425	Planeweld #1 (3)	1/8	70	Flat	105-110	20-22	6	None	10
426	Ditto	1/8	300	Flat	90-95	20-22	7	"	11
423	"	1/8	70	Vert. (up)	85-90	18-20	6	"	12
424	"	1/8	70	O'head	95-100	18-21	7	"	13
425	"	1/8	70	Flat	105-110	20-22	6	QD(4)	14
426	"	1/8	300	Flat	90-95	20-22	7	"	15
423	"	1/8	70	Vert. (up)	85-90	18-20	6	"	16
424	"	1/8	70	O'head	95-100	18-21	7	"	17

(1) All specimens welded manually.
(2) AWS class E6013; plain carbon steel deposit.
(3) Alloy aircraft type; alloy steel deposit.
(4) Quenched in oil after 30 min. at 1600-1650°F.; drawn 30 min. at 1000°F.

Under each of the 16 welding conditions above, eight flat tension specimens were prepared. Four specimens had a weld made in a continuous pass, and four were made with a weld interrupted by a prolonged arc break in the center of the weld. (see detail, Figure 1)

TABLE 3A. ULTIMATE TENSILE STRENGTH OF CONTINUOUS AND INTERRUPTED SINGLE-BEAD BUTT WELDS IN 1/8-INCH SAE 4130 SHEET

(Data from Figures 2 to 17, inclusive)

Position of Welding	Preheat °F.	Average Ultimate Tensile Strength, p.s.i. (1)							
		Carbon Steel Electrode				Alloy Steel Electrode			
		As Welded		Quenched and Drawn		As Welded		Quenched and Drawn	
		Cont.	Inter.	Cont.	Inter.	Cont.	Inter.	Cont.	Inter.
Flat	70	103,600	88,800	131,900	113,200	98,700	101,200	158,600	146,100
Flat	300	102,100	82,900	125,200	123,300	98,900	103,300	153,700	136,600
Vertical	70	102,200	83,600	150,100	132,300	103,100	99,200	143,600	130,700
Overhead	70	105,400	98,400	140,800	98,000	108,400	98,100	160,500	145,100

(1) Average UTS of unwelded plate, as received condition, was 97,500 p.s.i. (Mill).

107,300 p.s.i. (BMI)

TABLE 3B. SUMMARY OF TENSILE STRENGTH DATA

Electrode	Heat Treatment	Positions and Preheat	Joints with Continuous Welds	Joints with Interrupted Welds	Per Cent Decrease in Tensile Strength of Interrupted Welds
Carbon steel	As welded	All	103,300	88,400	15
Carbon steel	Q & D	All	137,000	116,700	15
Alloy steel	As welded	All	102,300	100,500	2
Alloy steel	Q & D	All	154,100	139,600	9
Both	As welded	All	102,800	94,500	8
Both	Q & D	All	145,600	128,200	12
Both	Both	All	124,200	111,300	10

TABLE 3C. LOCATION OF STATIC-TENSION FRACTURES IN BUTT-WELDED SPECIMENS IN 1/8-INCH SHEET

(See also Figures 2-17, inclusive)

Character of Weld	Electrode Used	Heat Treatment After Welding	Number of Tension Tests Made	Relative Number of Fractures: in Parent Plate	Relative Number of Fractures: in Weld	Relative Percentage of Fractures: in Parent Plate	Relative Percentage of Fractures: in Weld
Continuous	Carbon Steel	AW	16	6	10	38	62
		Q & D	16	0	16	0	100
	Alloy Steel	AW	16	12	4	75	25
		Q & D	11	2	9	18	82
	All conditions		59	20	39	34	66
Interrupted	Carbon Steel	AW	16	0	16	0	100
		Q & D	15	0	15	0	100
	Alloy Steel	AW	16	4	12	25	75
		Q & D	16	0	16	0	100
	All conditions		63	4	59	6	94

TABLE 4. WELDING DATA FOR CONTINUOUS AND INTERRUPTED-BEAD BUTT-WELDS IN 1/8-INCH SAE 4130 SHEET (1)

Test Number	Type of Weld Joint (2)	Reinforcement	Weld Bead	Electrode Diam., In.	Direct Current (Electrode Negative) Amperes	Arc Volts	Approximate Welding Speed, In./Min.	Radiographs in Figure:
584 (-1 to -6)	Two-bead, continuous.	Flush	Root #1 Face #2	5/64 1/8	40-45 85-90	20-22 20-22	8 7	21
584 (-7 to -12)	Two-bead, continuous.	Full	Root #1 Face #2	5/64 1/8	40-45 85-90	20-22 20-22	8 7	20
585 (-1 to -6)	Two-bead, continuous root interrupted face.	Flush	Root #1 Face #2	5/64 1/8	40-45 85-90	20-22 20-22	8 6	23
585 (-7 to -12)	Two-bead, continuous root interrupted face.	Full	Root #1 Face #2	5/64 1/8	40-45 85-90	20-22 20-22	8 6	22
586 (1, 2, 3)	Single-bead, continuous.	Full	Face #1	1/8	70-75	20-22	4-1/2	24
586 (4, 5, 6)	Single-bead, continuous.	Flush	Face #1	1/8	70-75	20-22	4-1/2	25
586 (7, 8, 9)	Single-bead, interrupted.	Full	Face #1	1/8	70-75	20-22	4	26
586 (10, 11, 12)	Single-bead, interrupted.	Flush	Face #1	1/8	70-75	20-22	4	27

(1) For chemical analysis see Table 1.

(2) All welding manual metal-arc, using Wilson 520 electrodes (AWS Class E6013); welds made in flat position, with initial plate temperature 300°F. All plates normalized before welding; no heat treatment after welding. For groove details see Figure 19.

TABLE 5. FATIGUE STRENGTH OF CONTINUOUS AND INTERRUPTED BUTT WELDS IN 1/8-INCH SAE 4130 SHEET

Test No.	Type Weld	Weld Section, Fig. 19	Reversed Bending Stress, p.s.i.	Cycles to Failure	Location of Failure	X-Ray in Figure:
584-7	Continuous, 2-bead, reinforced.	Group 1	57,500	69,000	Toe of 2nd weld bead.	21
-8			51,800	96,000	Ditto	
-12			51,800	121,000	"	
-9			45,300	160,000	"	
-10			37,000	234,000	"	
-11			28,600	869,000	"	
584-6	Continuous, 2-bead, flush.	Group 2	62,000	255,000	Unaffected plate (2).	22
-5			57,500	421,000	Fusion zone (2nd bead).	
-1			51,800	175,000	Center of weld.	
-2			45,300	600,000	Fusion zone (2nd bead).	
-3			37,000	2,116,000	Center of weld.	
-4			28,600	7,283,000	No failure.	
585-9	Interrupted, 2-bead, reinforced.	Group 3	62,100	30,000	Toe of 2nd weld bead.	23
-11			57,500	No record(1)	Ditto	
-7			51,800	60,000	"	
-8			45,300	56,000	"	
-10			37,000	No record(1)	"	
-12			28,600	451,000	"	
585-6	Interrupted, 2-bead, flush.	Group 4	57,500	123,000	Center of weld.	24
-5			51,800	155,000	Ditto	
-4			45,300	138,000	"	
-3			37,000	368,000	"	
-1			28,600	836,000	"	
-2			19,400	4,778,000	No failure.	
586-2	Continuous, 1-bead, reinforced.	Group 5	51,800	100,000	Toe of weld bead.	25
-1			45,300	147,000	Ditto	
-3			28,600	2,994,000	"	
586-6	Continuous, 1-bead, flush.	Group 6	54,200	100,000	Unaffected plate(2).	26
-4			45,000	200,000	Ditto	
-5			45,000	226,000	"	
586-8	Interrupted, 1-bead, reinforced.	Group 7	62,200	43,000	Toe of weld bead.	27
-9			62,200	46,000	Ditto	
-7			37,000	614,000	"	
586-12	Interrupted, 1-bead, flush.	Group 8	54,700	93,000	Center of weld.	28
-10			45,000	148,000	Ditto	
-11			24,700	1,004,000	"	

(1) Testing machine kept running after failure.
(2) At change of section from taper to radius.

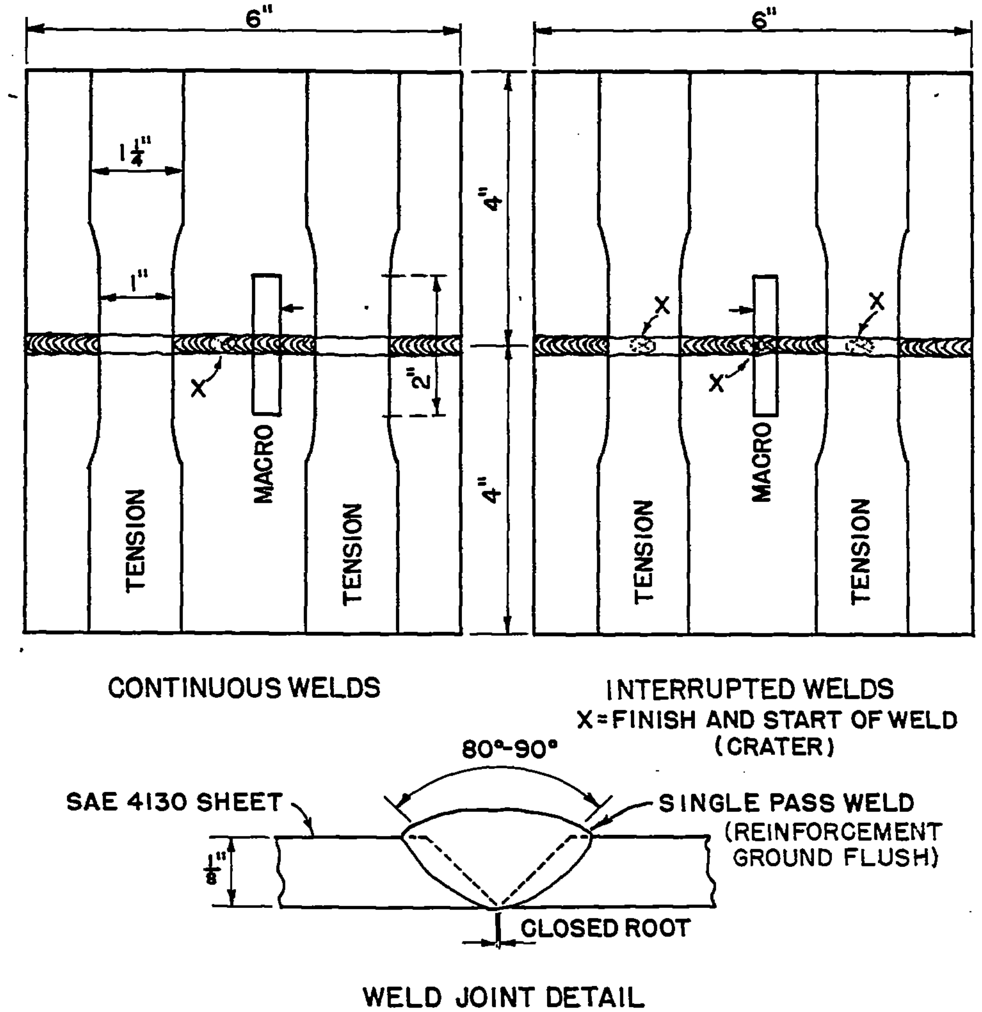
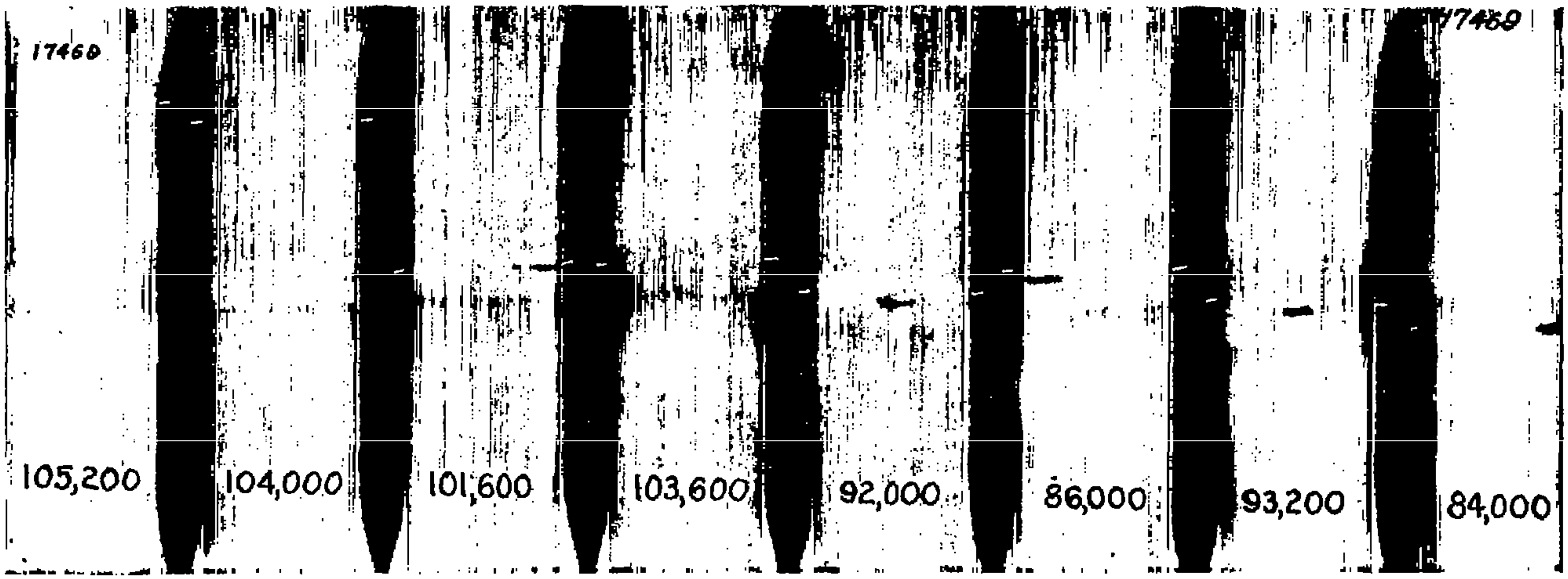


FIGURE 1 –

BUTT-WELDED SPECIMEN FOR STATIC TENSION TESTS OF JOINTS WITH CONTINUOUS AND INTERRUPTED WELDS.



17469

Figure 2.—Radiograph of metal-arc-welded static tension specimens in 1/8-inch SAE 4130 sheet.

Four specimens at left made with continuous weld.

Four specimens at right made with interrupted weld (includes finish and start of weld bead).

Ultimate tensile strength, p. s. i., shown for each specimen.

Transverse lines indicate location of fracture.

Test No. 419:

Weld joint: Single-layer weld in 90° single-vee groove; no root clearance; no backing; manual weld.

Electrode: 1/8-inch carbon steel; 110–115 amperes; 19–21 volts; negative direct current.

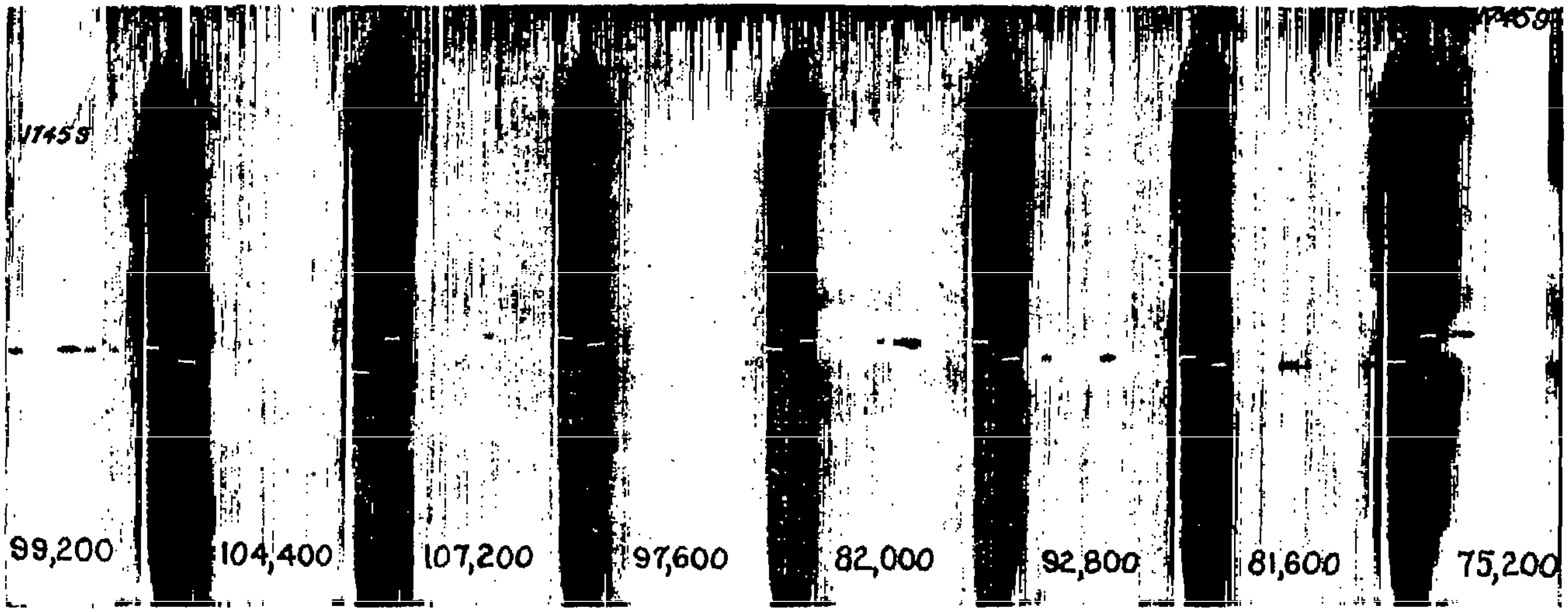
Speed: 7 inches per minute.

Position: Flat.

Initial plate temperature: 70° F.

Heat treatment after welding: As welded.

Reinforcement ground flush.



17459

Figure 3.—Radiograph of metal-arc-welded static tension specimens in ⅛-inch SAE 4130 sheet.

Four specimens at left made with continuous weld.

Four specimens at right made with interrupted weld (includes finish and start of weld bead).

Ultimate tensile strength, p. s. i., shown for each specimen.

Transverse lines indicate location of fracture.

Test No. 420:

Weld joint: Single-layer weld in 90° single-vee groove; no root clearance; no backing; manual weld.

Electrode: ⅛-inch carbon steel; 105–110 amperes; 20–22 volts; negative direct current.

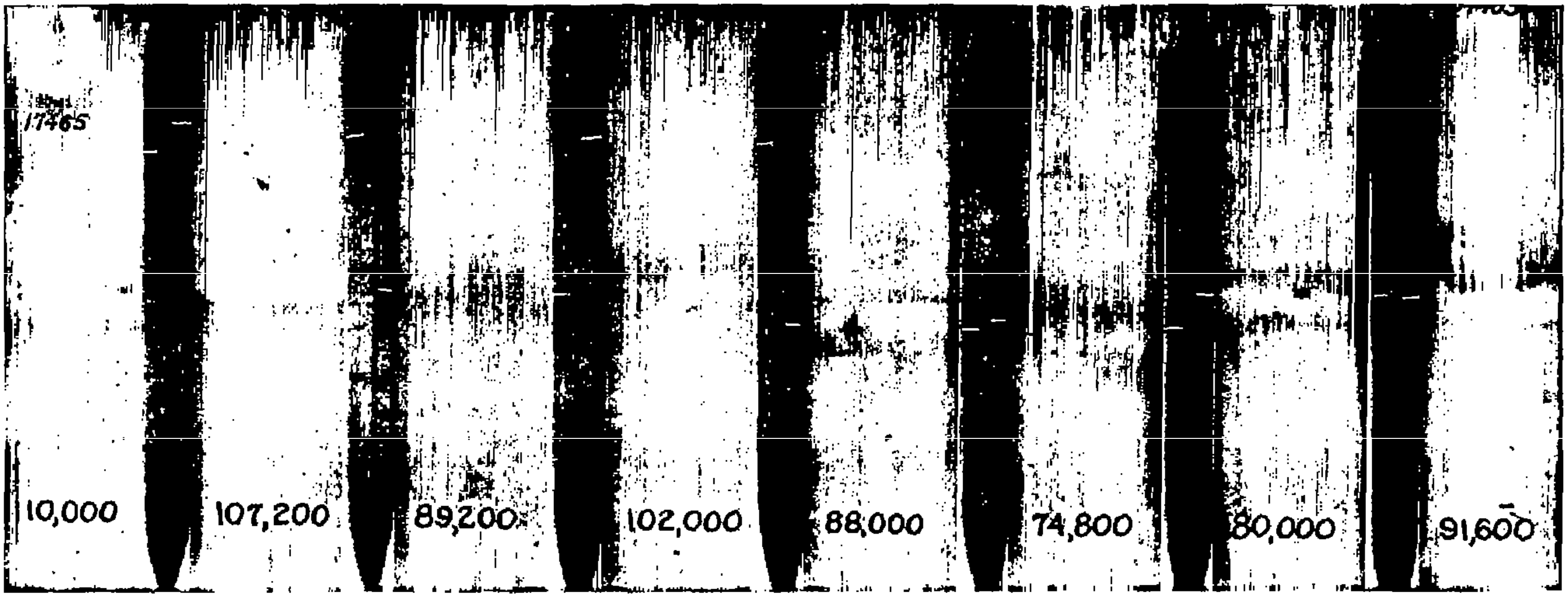
Speed: 8 inches per minute.

Position: Flat.

Initial plate temperature: 300° F.

Heat treatment after welding: As welded.

Reinforcement ground flush.



17465

Figure 4.—Radiograph of metal-arc-welded static tension specimens in ⅛-inch SAE 4130 sheet.

Four specimens at left made with continuous weld.

Four specimens at right made with interrupted weld (includes finish and start of weld bead).

Ultimate tensile strength, p. s. i., shown for each specimen.

Transverse lines indicate location of fracture.

Test No. 421:

Weld joint: Single-layer weld in 90° single-vee groove; no root clearance; no backing; manual weld.

Electrode: $\frac{5}{32}$-inch carbon steel; 70–75 amperes; 21–23 volts; negative direct current.

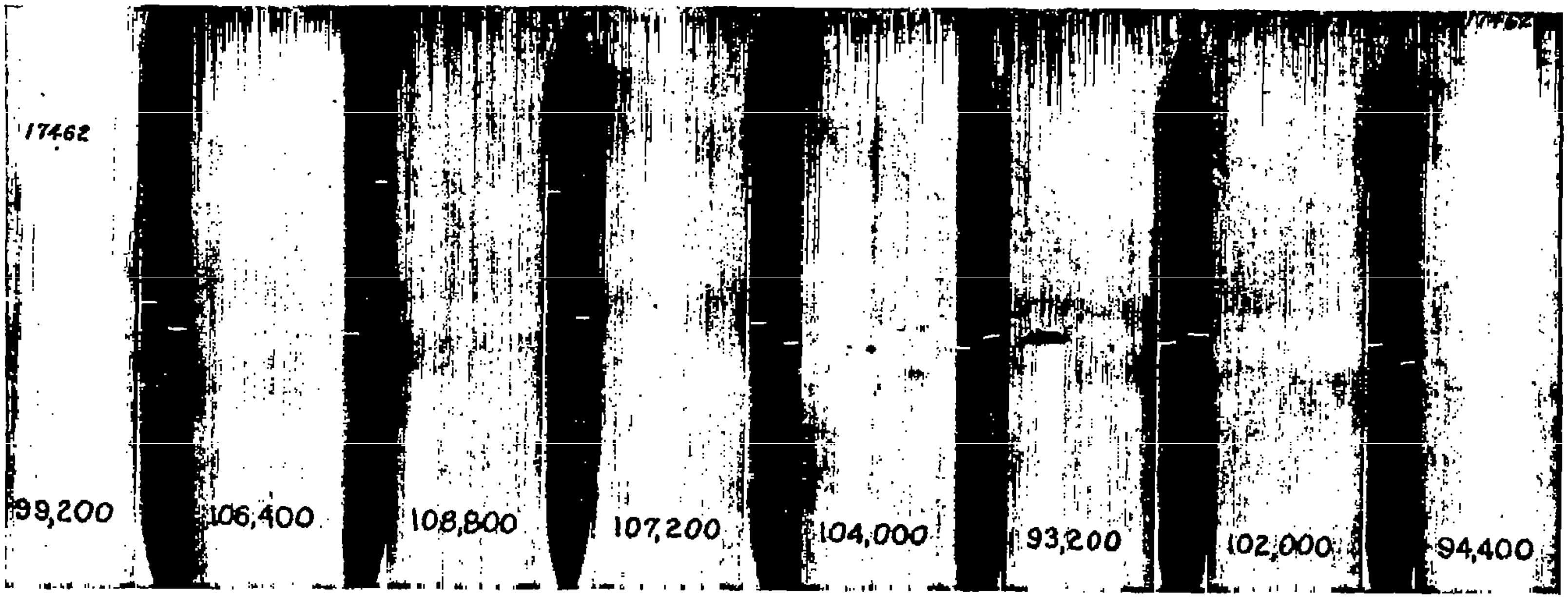
Speed: 6 inches per minute.

Position: Vertical (up).

Initial plate temperature: 70° F.

Heat treatment after welding: As welded.

Reinforcement ground flush.



17462

Figure 5.—Radiograph of metal-arc-welded static tension specimens in 1/8-inch SAE 4130 sheet.

Four specimens at left made with continuous weld.

Four specimens at right made with interrupted weld (includes finish and start of weld bead).

Ultimate tensile strength, p. s. i., shown for each specimen.

Transverse lines indicate location of fracture.

Test No. 422:

Weld joint: Single-layer weld in 90° single-vee groove; no root clearance; no backing; manual weld.

Electrode: 1/8-inch carbon steel; 105–110 amperes; 19–22 volts; negative direct current.

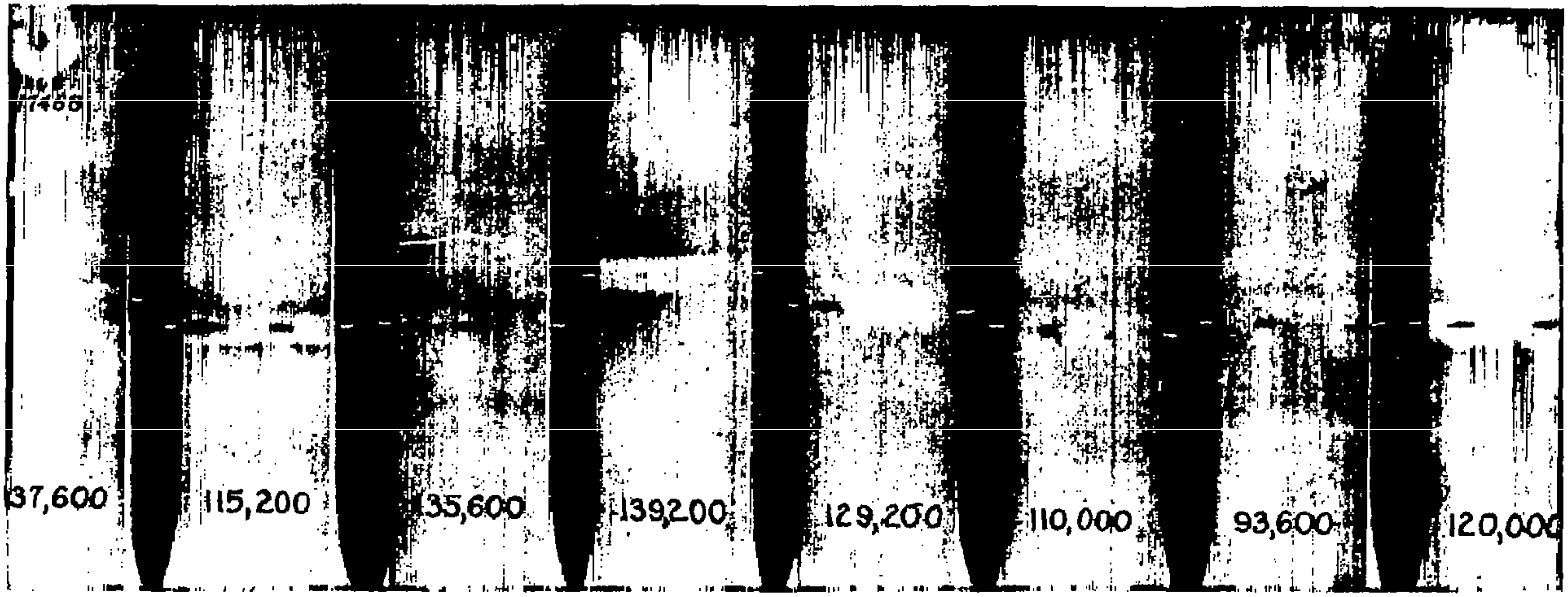
Speed: Not recorded.

Position: Overhead.

Initial plate temperature: 70° F.

Heat treatment after welding: As welded.

Reinforcement ground flush.



17468

Figure 6.—Radiograph of metal-arc-welded static tension specimens in $\frac{1}{8}$-inch SAE 4130 sheet.

Four specimens at left made with continuous weld.

Four specimens at right made with interrupted weld (includes finish and start of weld bead).

Ultimate tensile strength, p. s. i., shown for each specimen.

Transverse lines indicate location of fracture.

Test No. 419:

Weld joint: Single-layer weld in 90° single-vee groove; no root clearance; no backing; manual weld.

Electrode: $\frac{1}{8}$-inch carbon steel; 110–115 amperes; 19–21 volts; negative direct current.

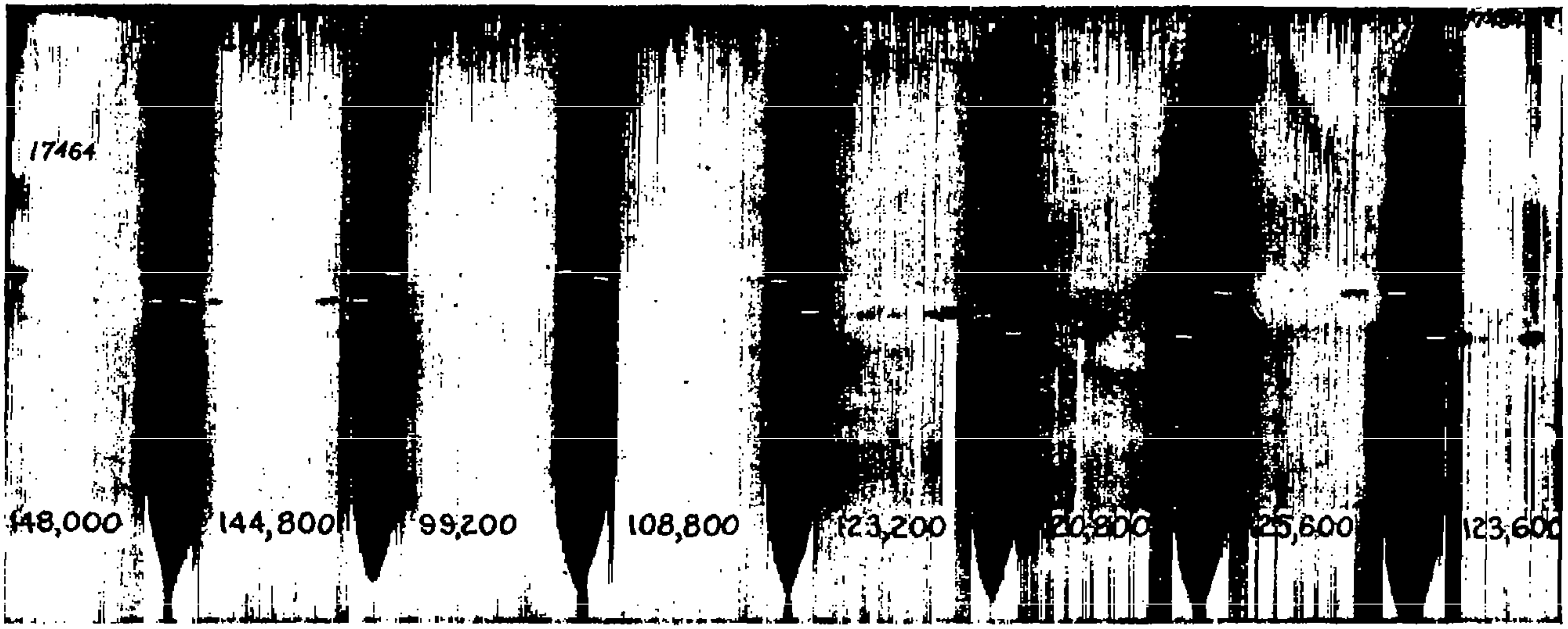
Speed: 7 inches per minute.

Position: Flat.

Initial plate temperature: 70° F.

Heat treatment after welding: Quenched and drawn.

Reinforcement ground flush.



17464

Figure 7.—Radiograph of metal-arc-welded static tension specimens in 1/8-inch SAE 4130 sheet.

Four specimens at left made with continuous weld.

Four specimens at right made with interrupted weld (includes finish and start of weld bead).

Ultimate tensile strength, p. s. i., shown for each specimen.

Transverse lines indicate location of fracture.

Test No. 420:

Weld joint: Single-layer weld in 90° single-vee groove; no root clearance; no backing; manual weld.

Electrode: 1/8-inch carbon steel; 105–110 amperes; 20–22 volts; negative direct current.

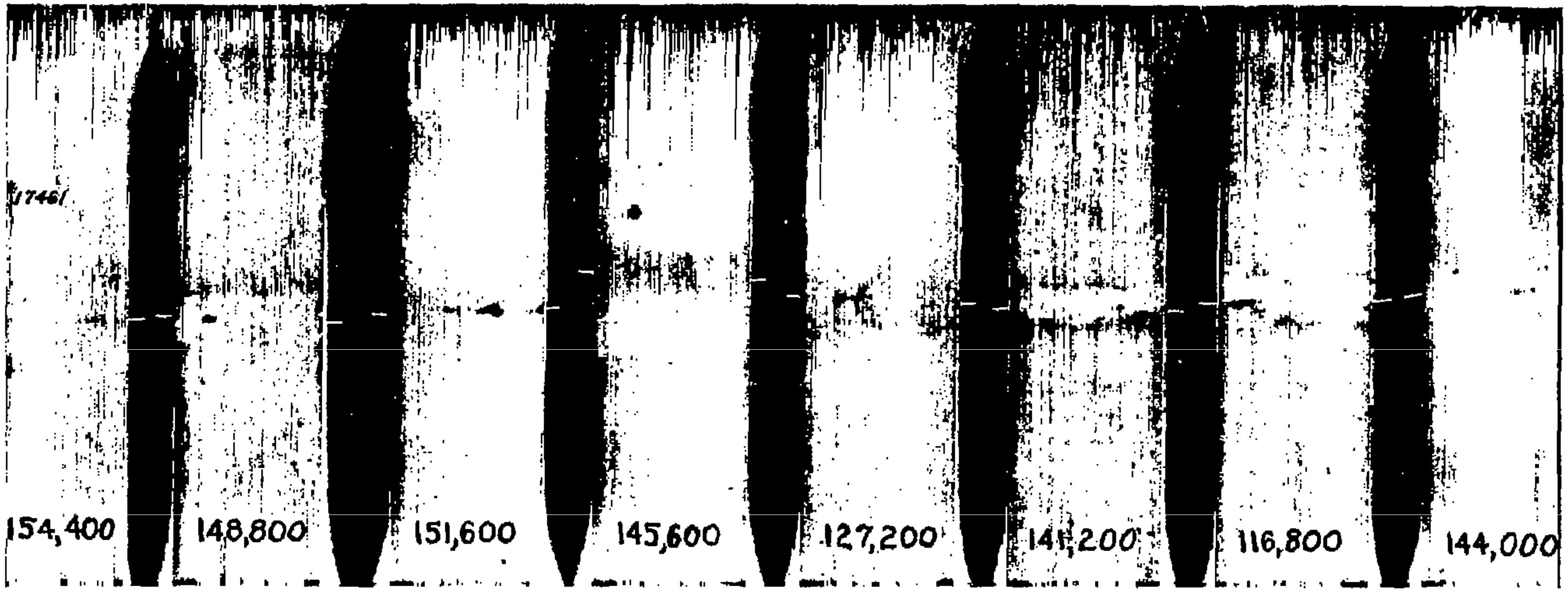
Speed: 8 inches per minute.

Position: Flat.

Initial plate temperature: 300° F.

Heat treatment after welding: Quenched and drawn.

Reinforcement ground flush.



17461

Figure 8.—Radiograph of metal-arc-welded static tension specimens in 1/8-inch SAE 4130 sheet.

Four specimens at left made with continuous weld.

Four specimens at right made with interrupted weld (includes finish and start of weld bead).

Ultimate tensile strength, p. s. i., shown for each specimen.

Transverse lines indicate location of fracture.

Test No. 421:

Weld joint: Single-layer weld in 90° single-vee groove; no root clearance; no backing; manual weld.

Electrode: 5/32-inch carbon steel; 70–75 amperes; 21–23 volts; negative direct current.

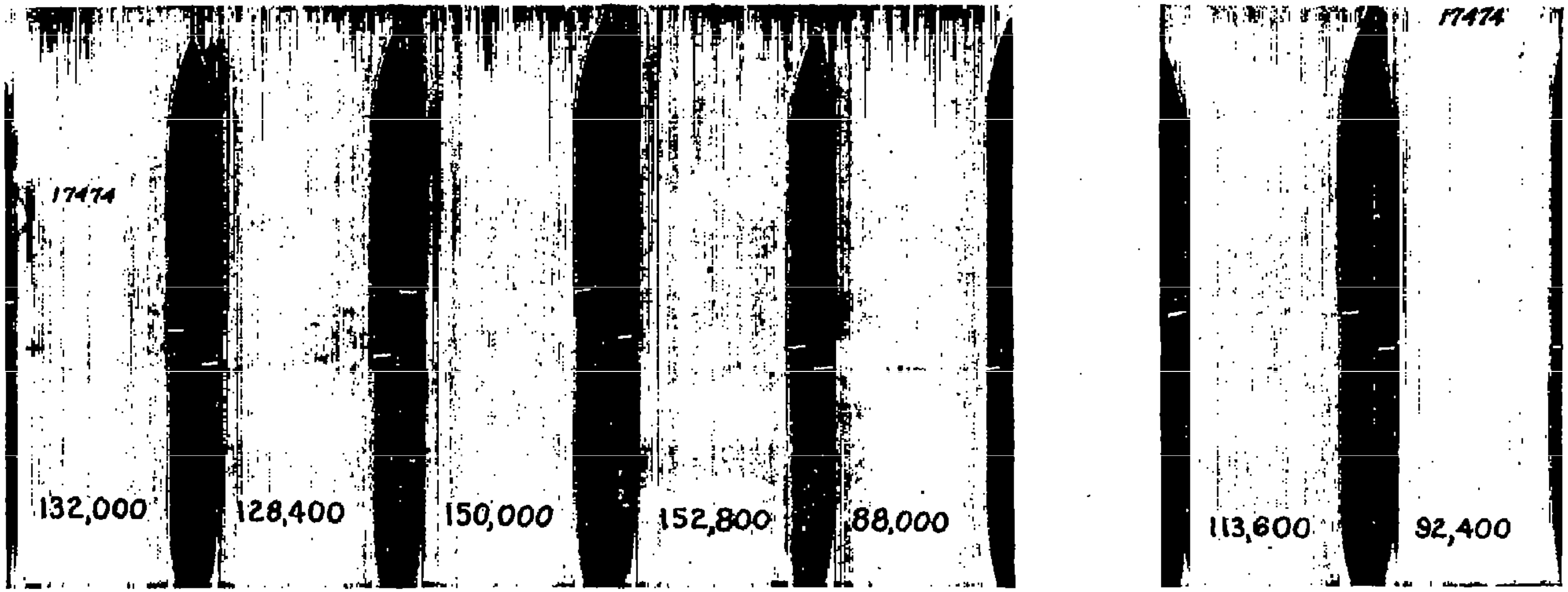
Speed: 6 inches per minute.

Position: Vertical (up).

Initial plate temperature: 70° F.

Heat treatment after welding: Quenched and drawn.

Reinforcement ground flush.



17474

Figure 9.—Radiograph of metal-arc-welded static tension specimens in ⅛-inch SAE 4130 sheet.

Four specimens at left made with continuous weld.

Three specimens at right made with interrupted weld (includes finish and start of weld bead).

Ultimate tensile strength, p. s. i., shown for each specimen.

Transverse lines indicate location of fracture.

Test No. 422:

Weld joint: Single-layer weld in 90° single-vee groove; no root clearance; no backing; manual weld.

Electrode: ⅛-inch carbon steel; 105–110 amperes; 19–22 volts; negative direct current.

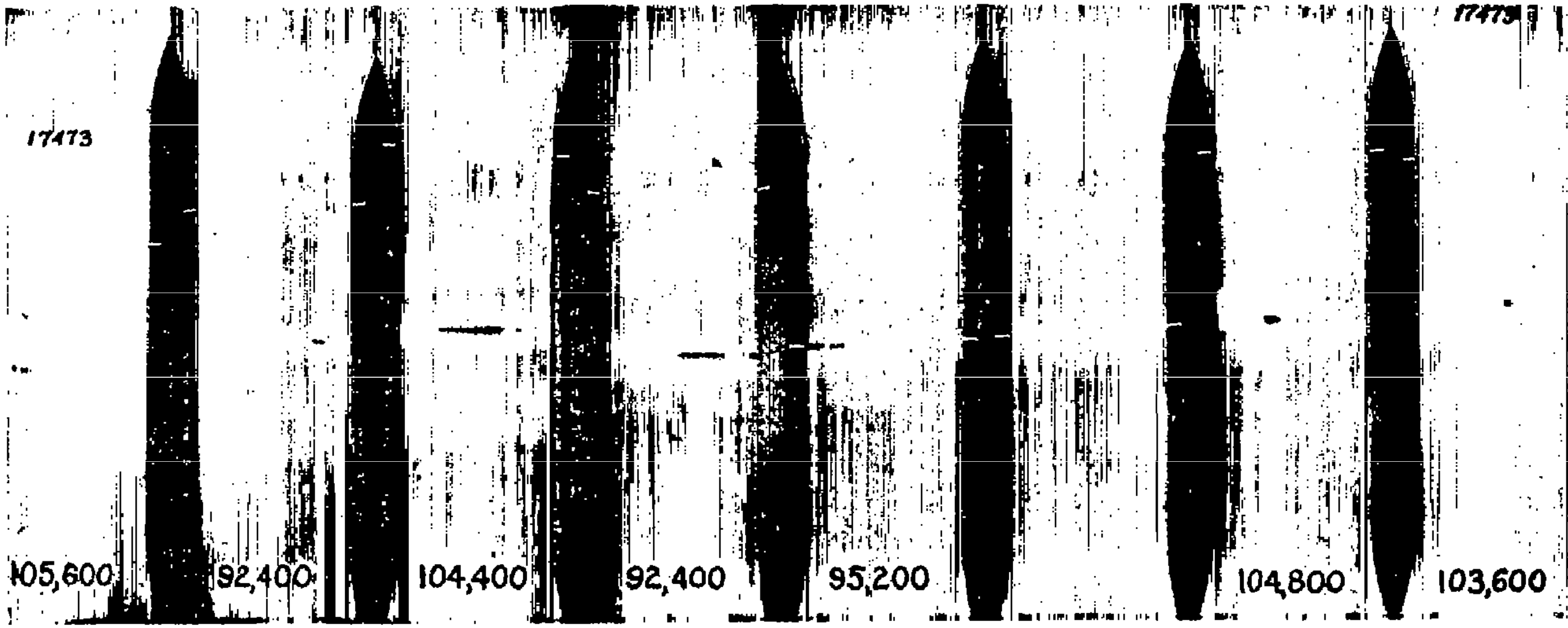
Speed: Not recorded.

Position: Overhead.

Initial plate temperature: 70° F.

Heat treatment after welding: Quenched and drawn.

Reinforcement ground flush.



17473

Figure 10.—Radiograph of metal-arc-welded static tension specimens in ⅛-inch SAE 4130 sheet.

Four specimens at left made with continuous weld.

Four specimens at right made with interrupted weld (includes finish and start of weld bead).

Ultimate tensile strength, p. s. i., shown for each specimen.

Transverse lines indicate location of fracture.

Test No. 425:

Weld joint: Single-layer weld in 90° single-vee groove; no root clearance; no backing; manual weld.

Electrode: ⅛-inch alloy steel; 105–110 amperes; 20–22 volts; negative direct current.

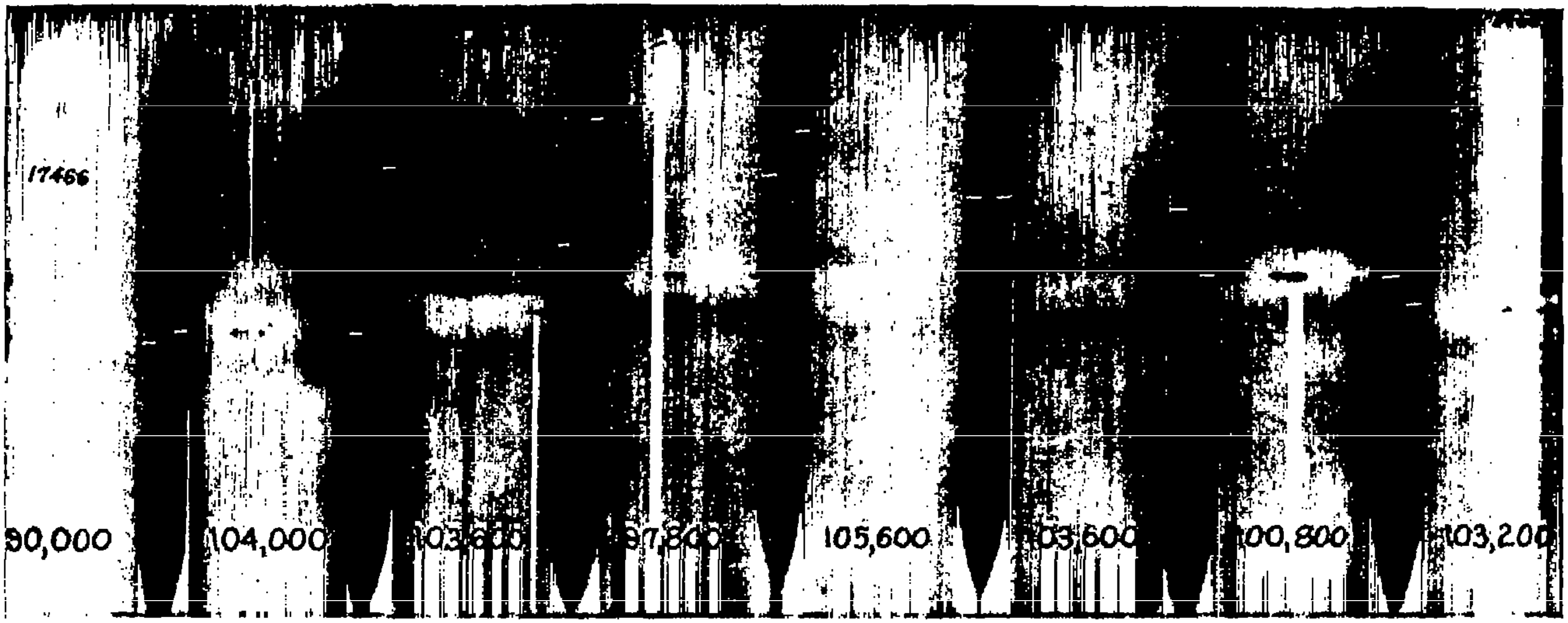
Speed: 6 inches per minute.

Position: Flat.

Initial plate temperature: 70° F.

Heat treatment after welding: As welded.

Reinforcement ground flush.



17466

Figure 11.—Radiograph of metal-arc-welded static tension specimens in ⅛-inch SAE 4130 sheet.

Four specimens at left made with continuous weld.

Four specimens at right made with interrupted weld (includes finish and start of weld bead).

Ultimate tensile strength, p. s. i., shown for each specimen.

Transverse lines indicate location of fracture.

Test No. 426:

Weld joint: Single-layer weld in 90° single-vee groove; no root clearance; no backing; manual weld.

Electrode: ⅛-inch alloy steel; 90–95 amperes; 20–22 volts; negative direct current.

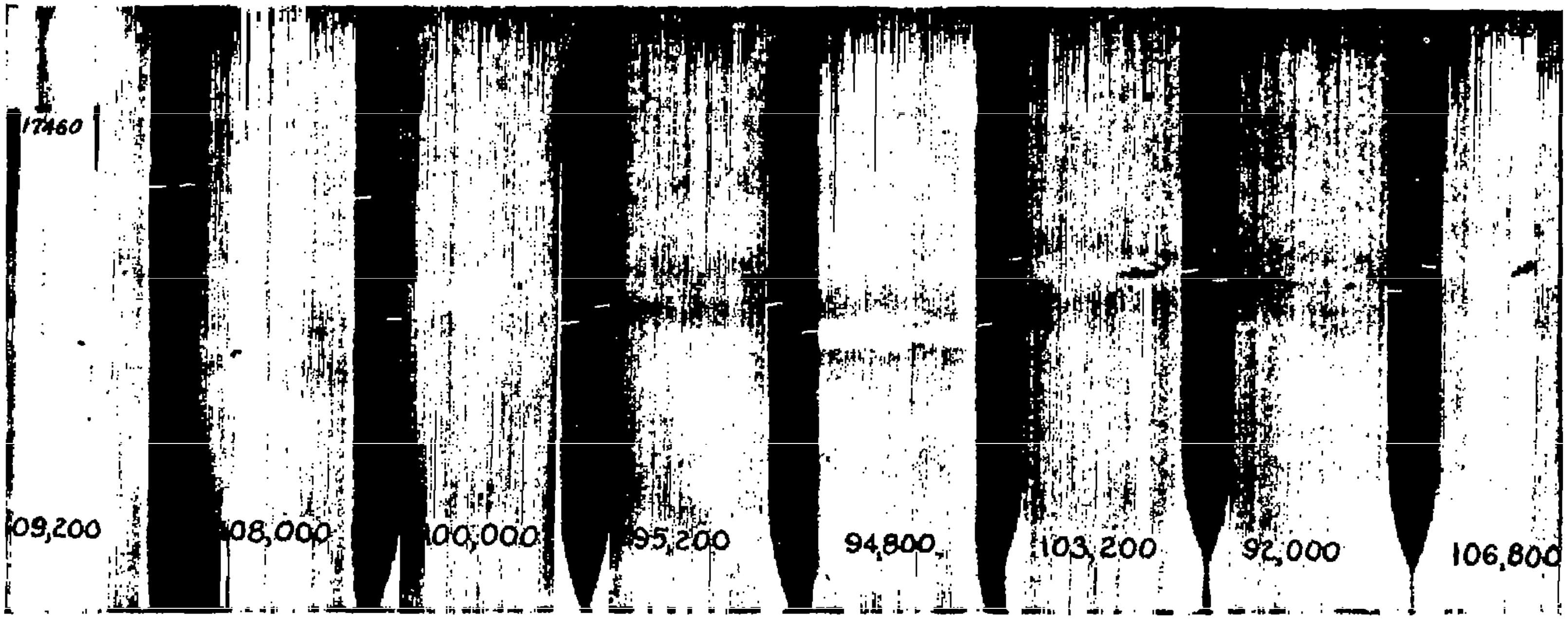
Speed: 7 inches per minute.

Position: Flat.

Initial plate temperature: 300° F.

Heat treatment after welding: As welded.

Reinforcement ground flush.



17460

Figure 12.—Radiograph of metal-arc-welded static tension specimens in 1/8-inch SAE 4130 sheet.

Four specimens at left made with continuous weld.

Four specimens at right made with interrupted weld (includes finish and start of weld bead).

Ultimate tensile strength, p. s. i., shown for each specimen.

Transverse lines indicate location of fracture.

Test No. 423:

Weld joint: Single-layer weld in 90° single-vee groove; no root clearance; no backing; manual weld.

Electrode: 1/8-inch alloy steel; 85–90 amperes; 18–20 volts; negative direct current.

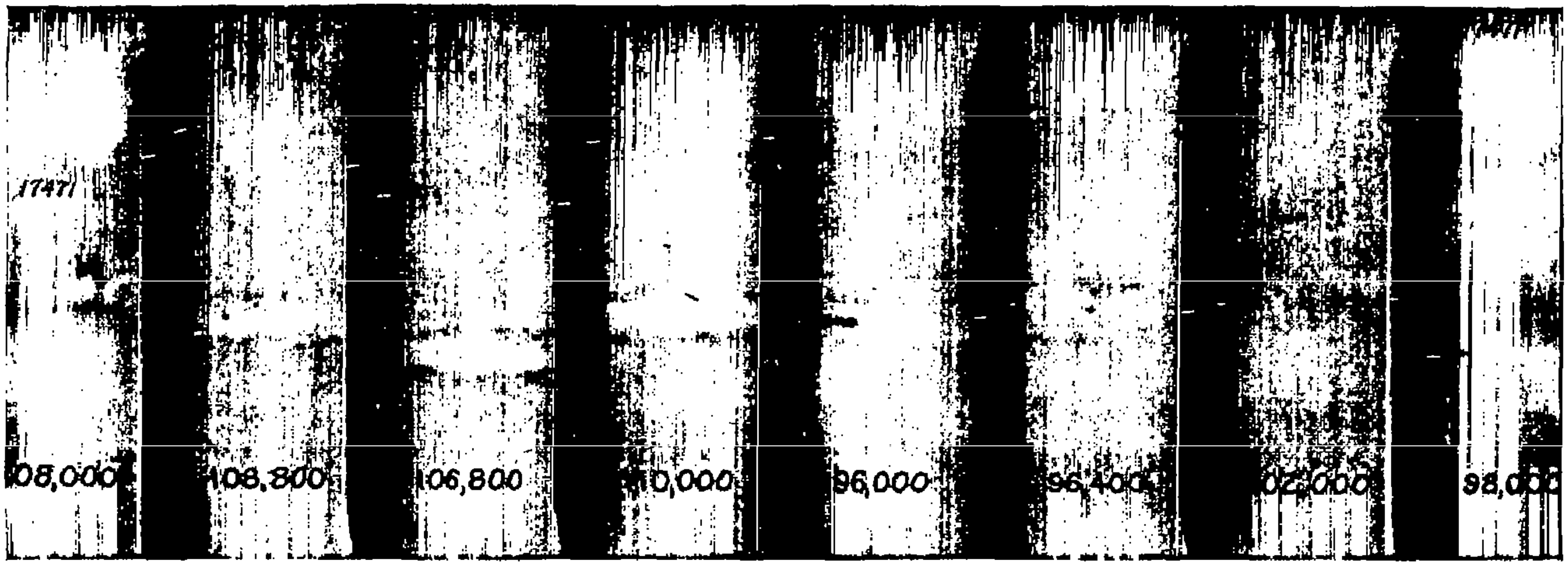
Speed: 6 inches per minute.

Position: Vertical (up).

Initial plate temperature: 70° F.

Heat treatment after welding: As welded.

Reinforcement ground flush.



17471

Figure 13.—Radiograph of metal-arc-welded static tension specimens in ⅛-inch SAE 4130 sheet.

Four specimens at left made with continuous weld.

Four specimens at right made with interrupted weld (includes finish and start of weld bead).

Ultimate tensile strength, p. s. i., shown for each specimen.

Transverse lines indicate location of fracture.

Test No. 424:

Weld joint: Single-layer weld in 90° single-vee groove; no root clearance; no backing; manual weld.

Electrode: ⅛-inch alloy steel; 95–100 amperes; 18–21 volts; negative direct current.

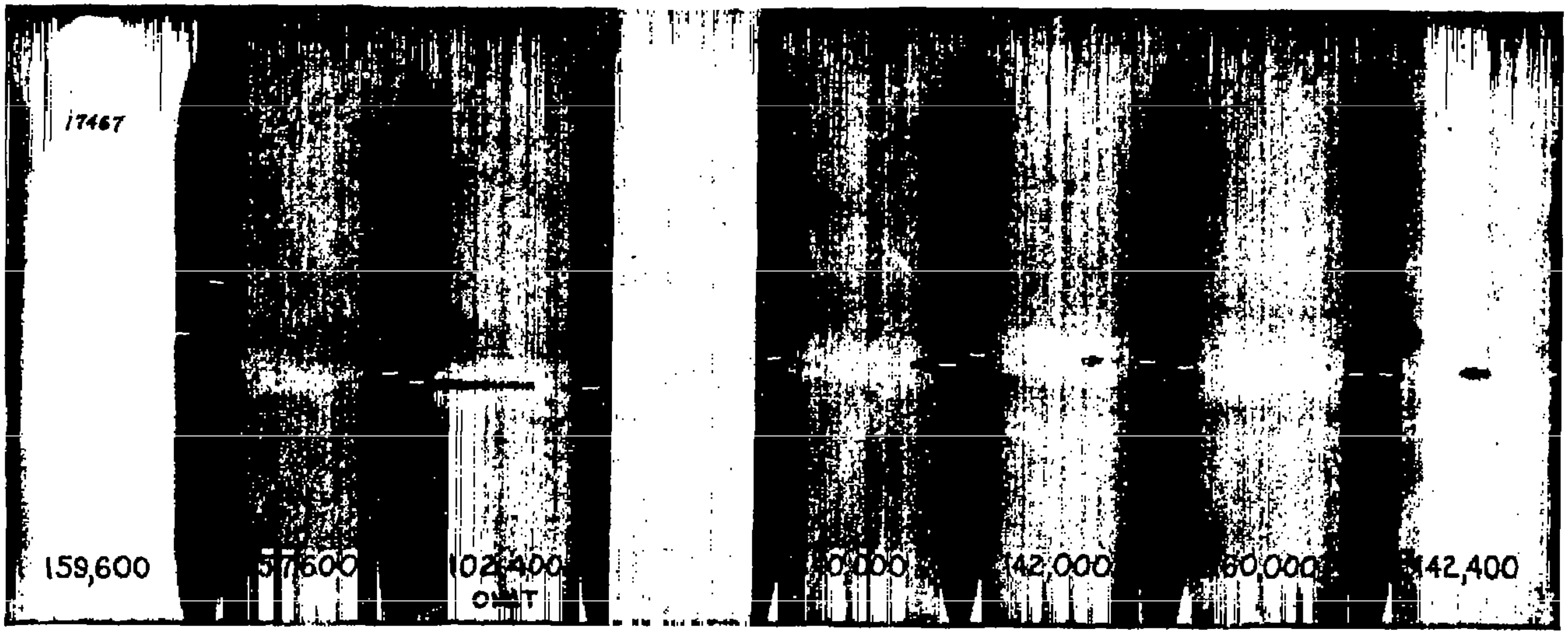
Speed: 7 inches per minute.

Position: Overhead.

Initial plate temperature: 70° F.

Heat treatment after welding: As welded.

Reinforcement ground flush.



17467

Figure 14.—Radiograph of metal-arc-welded static tension specimens in 1/8-inch SAE 4130 sheet.

Three specimens at left made with continuous weld.

Four specimens at right made with interrupted weld (includes finish and start of weld bead).

Ultimate tensile strength, p. s. i., shown for each specimen.

Transverse lines indicate location of fracture.

Test No. 425:

Weld joint: Single-layer weld in 90° single-vee groove; no root clearance; no backing; manual weld.

Electrode: 1/8-inch alloy steel; 105–110 amperes; 20–22 volts; negative direct current.

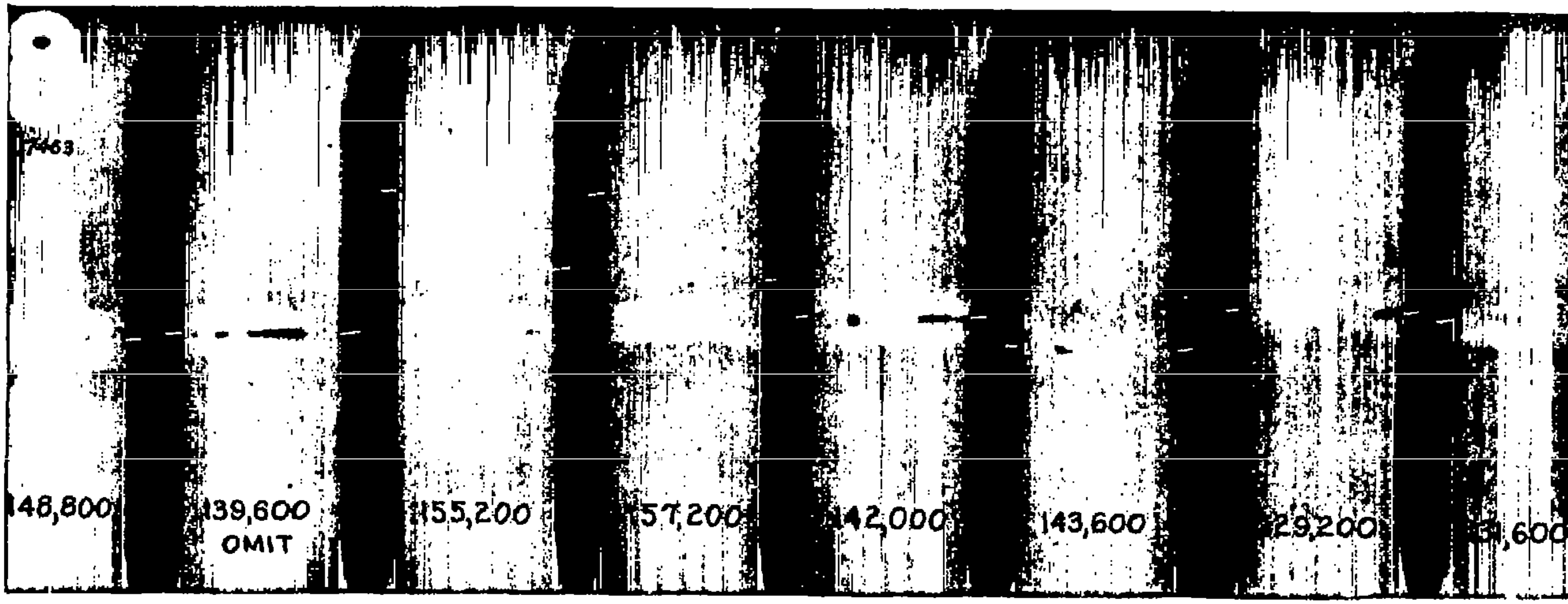
Speed: 6 inches per minute.

Position: Flat.

Initial plate temperature: 70° F.

Heat treatment after welding: Quenched and drawn.

Reinforcement ground flush.



17463

Figure 15.—Radiograph of metal-arc-welded static tension specimens in 1/8-inch SAE 4130 sheet.

Four specimens at left made with continuous weld.

Four specimens at right made with interrupted weld (includes finish and start of weld bead).

Ultimate tensile strength, p. s. i., shown for each specimen.

Transverse lines indicate location of fracture.

Test No. 426:

Weld joint: Single-layer weld in 90° single-vee groove; no root clearance; no backing; manual weld.

Electrode: 1/8-inch alloy steel; 90–95 amperes; 20–22 volts; negative direct current.

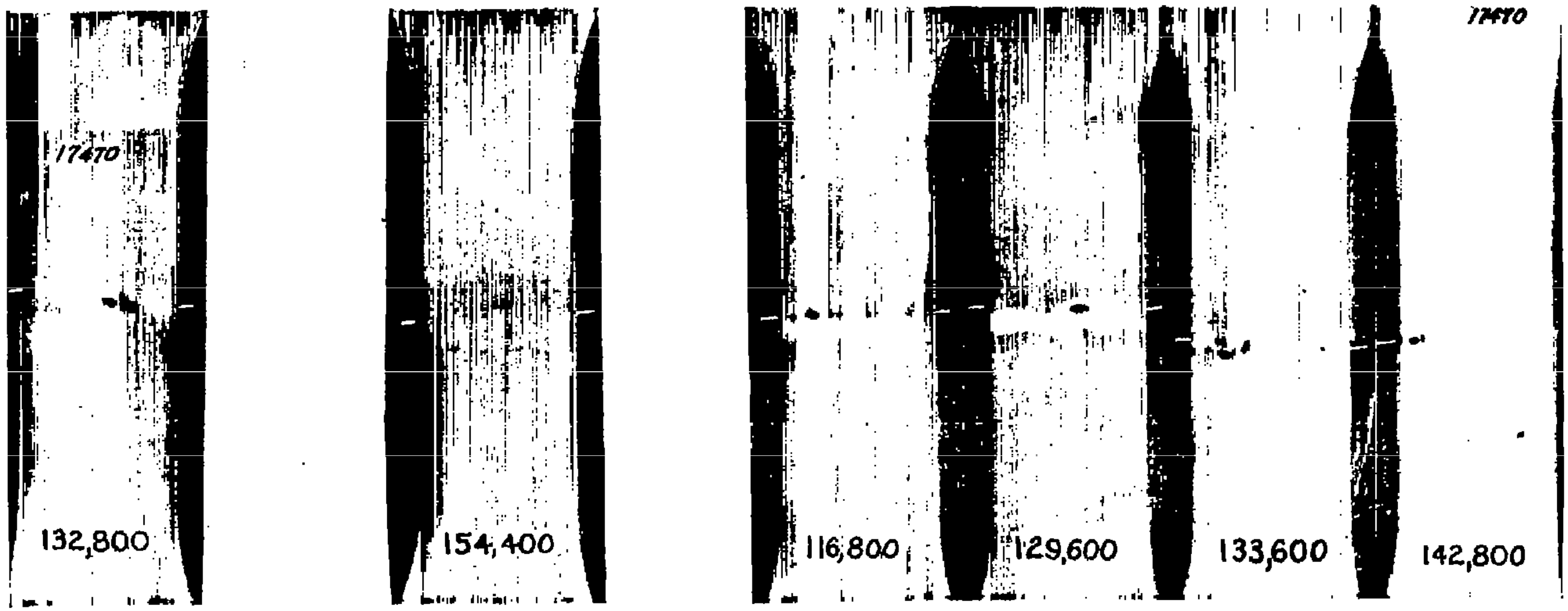
Speed: 7 inches per minute.

Position: Flat.

Initial plate temperature: 300° F.

Heat treatment after welding: Quenched and drawn.

Reinforcement ground flush.



17470

Figure 16.—Radiograph of metal-arc-welded static tension specimens in ⅛-inch SAE 4130 sheet.

Two specimens at left made with continuous weld.

Four specimens at right made with interrupted weld (includes finish and start of weld bead).

Ultimate tensile strength, p. s. i., shown for each specimen.

Transverse lines indicate location of fracture.

Test No. 423:

Weld joint: Single-layer weld in 90° single-vee groove; no root clearance; no backing; manual weld.

Electrode: ⅛-inch alloy steel; 85–90 amperes; 18–20 volts; negative direct current.

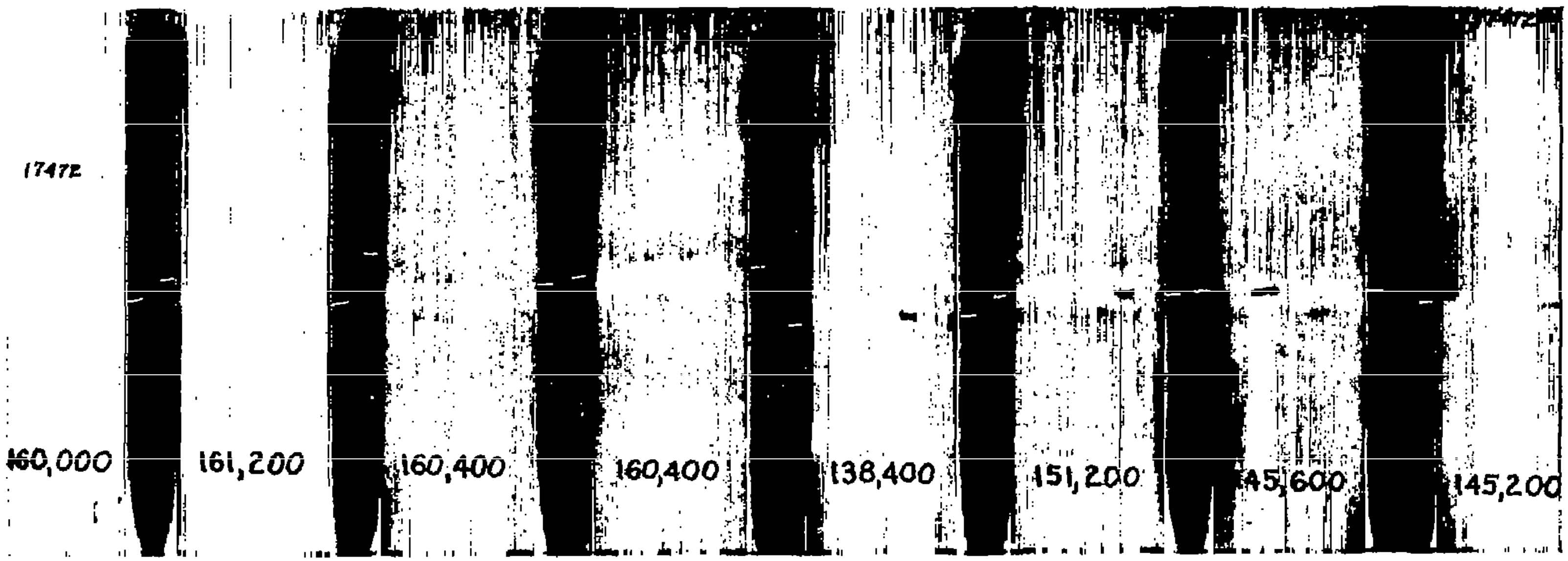
Speed: 6 inches per minute.

Position: Vertical (up).

Initial plate temperature: 70° F.

Heat treatment after welding: Quenched and drawn.

Reinforcement ground flush.



17472

Figure 17.—Radiograph of metal-arc-welded static tension specimens in ⅛-inch SAE 4130 sheet.

Four specimens at left made with continuous weld.

Four specimens at right made with interrupted weld (includes finish and start of weld bead).

Ultimate tensile strength, p. s. i., shown for each specimen.

Transverse lines indicate location of fracture.

Test No. 424:

Weld joint: Single-layer weld in 90° single-vee groove; no root clearance; no backing; manual weld.

Electrode: ⅛-inch alloy steel; 95–100 amperes; 18–21 volts; negative direct current.

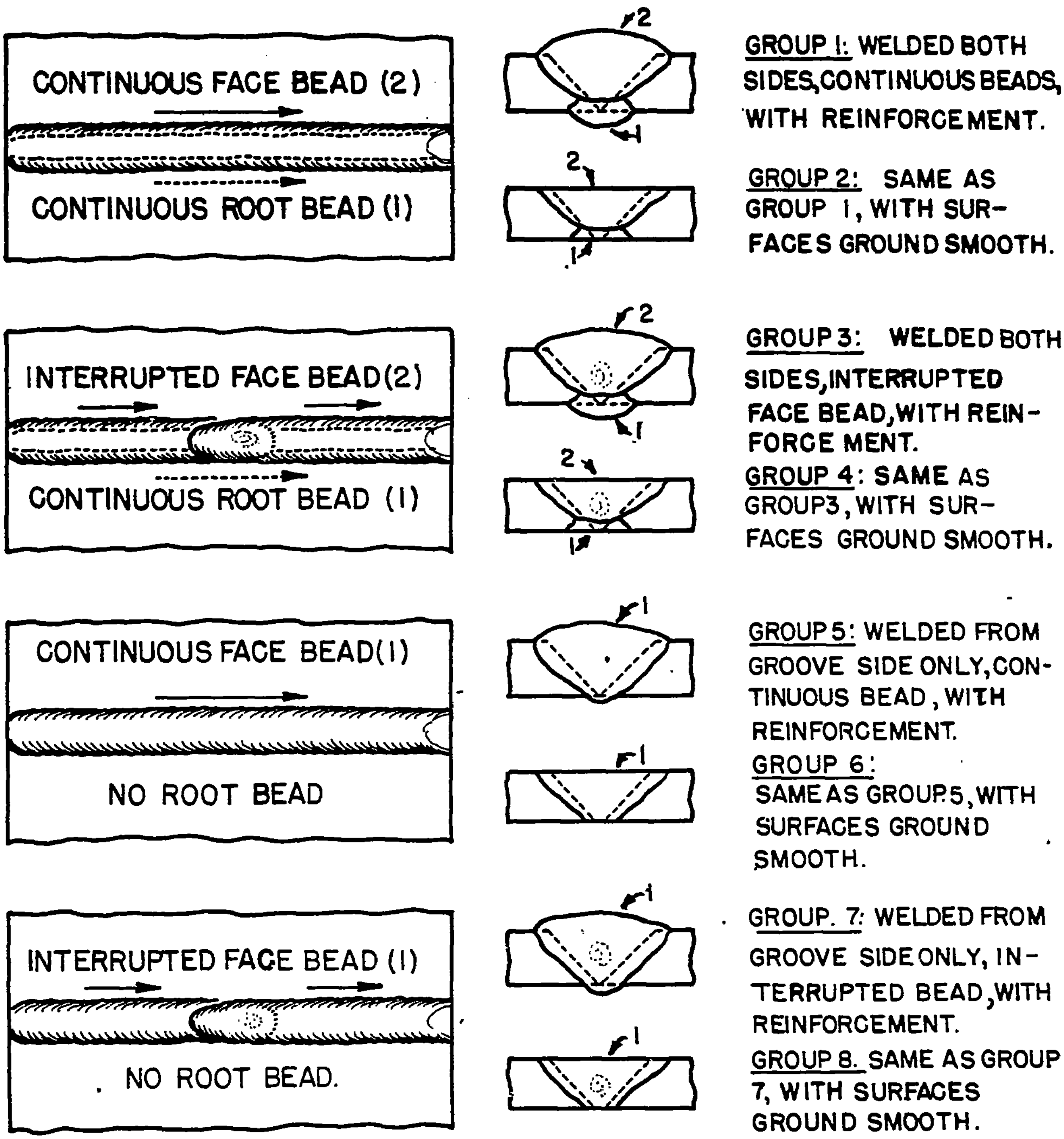
Speed: 7 inches per minute.

Position: Overhead.

Initial plate temperature: 70° F.

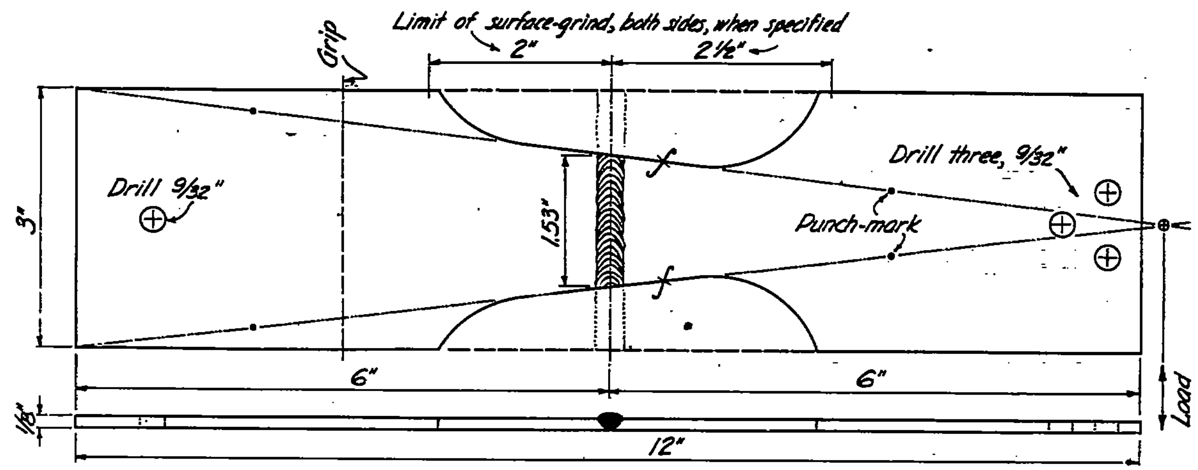
Heat treatment after welding: Quenched and drawn.

Reinforcement ground flush.

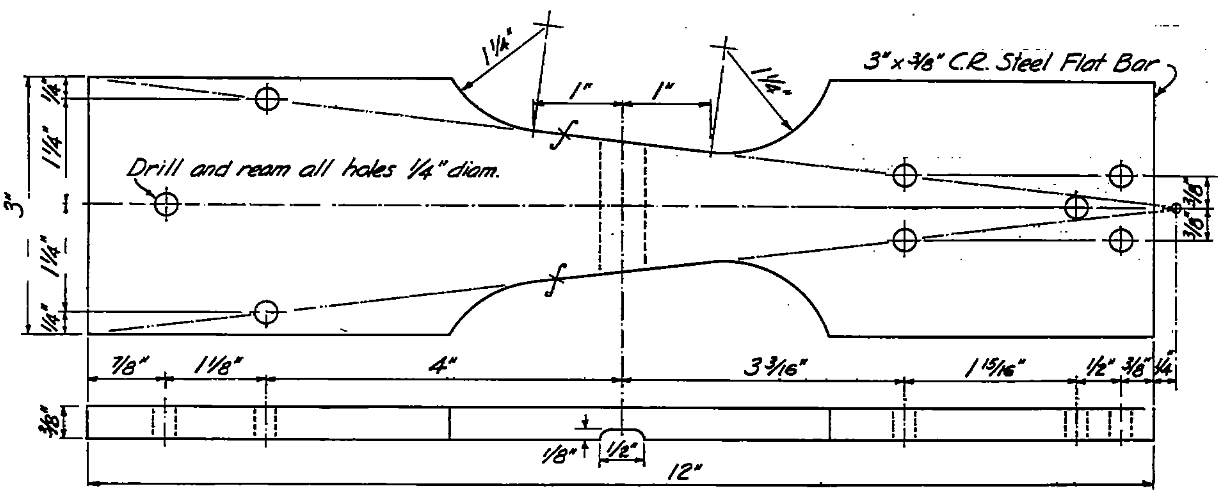


FOR ALL GROUPS, JOINT WAS 90-DEGREE SINGLE-VEE BUTT, CLOSED ROOT, WITH ALL WELDING DONE IN THE FLAT POSITION. FOR JOINTS WELDED FROM BOTH SIDES THE ROOT BEAD, 1, WAS WELDED FIRST, FROM THE ROOT SIDE.

FIGURE 18 - DETAIL OF WELD JOINT IN 1/8-INCH STEEL PLATE SPECIMEN FOR BENDING - FATIGUE TESTS.

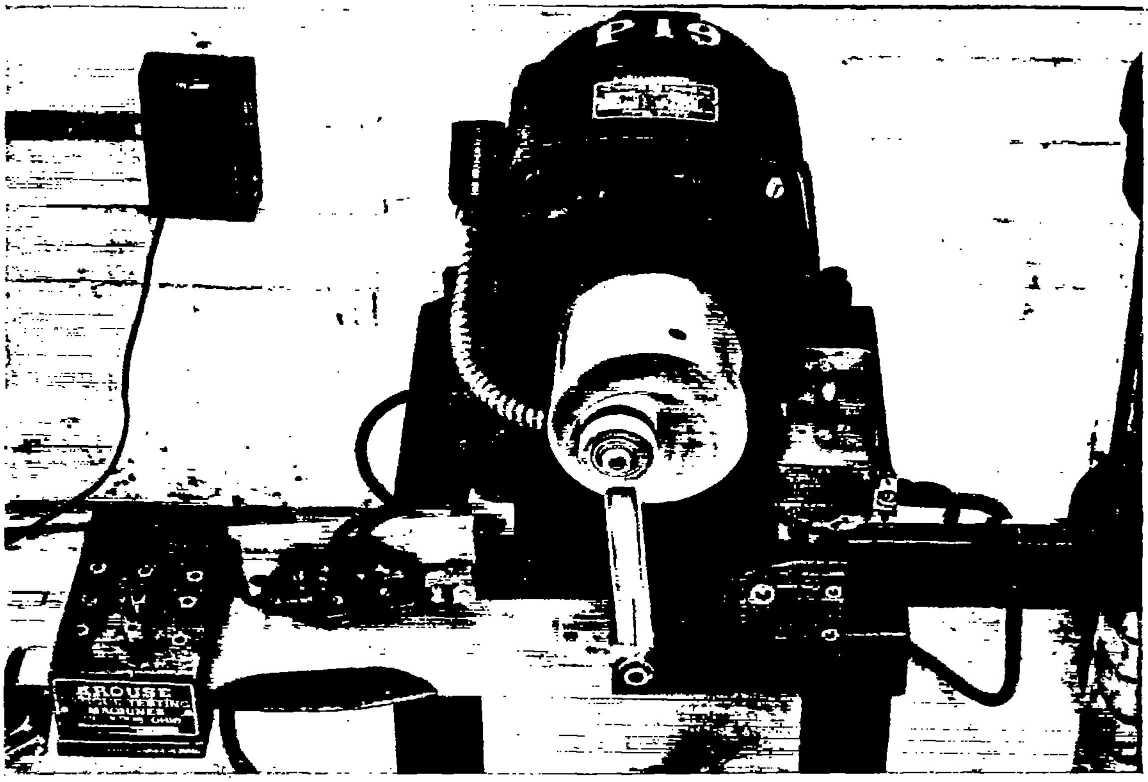


WELDED FATIGUE-TEST SPECIMEN



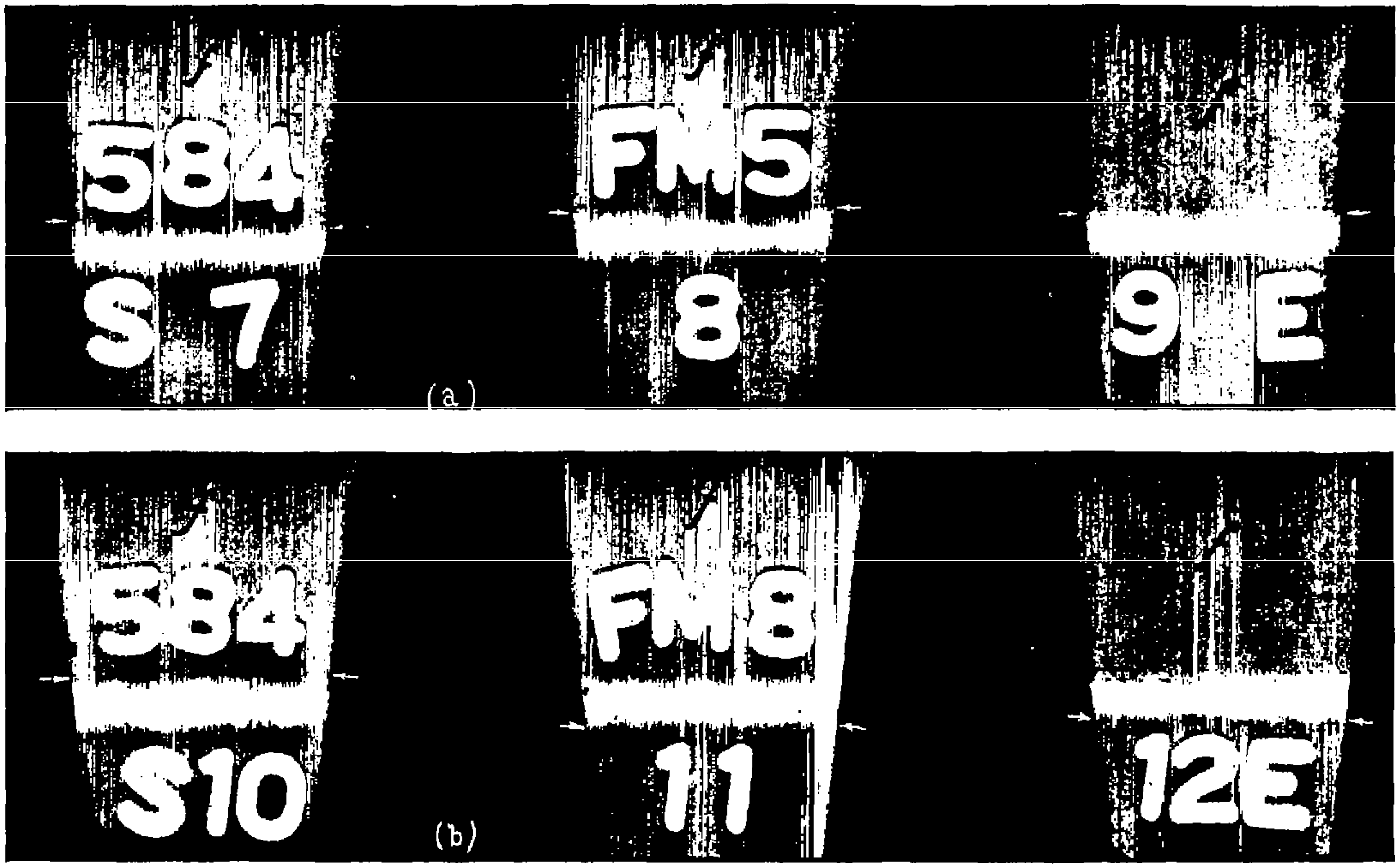
TEMPLET FOR FATIGUE-TEST SPECIMEN

FIGURE 19 - SPECIMEN AND TEMPLET FOR PLATE BENDING-FATIGUE TEST



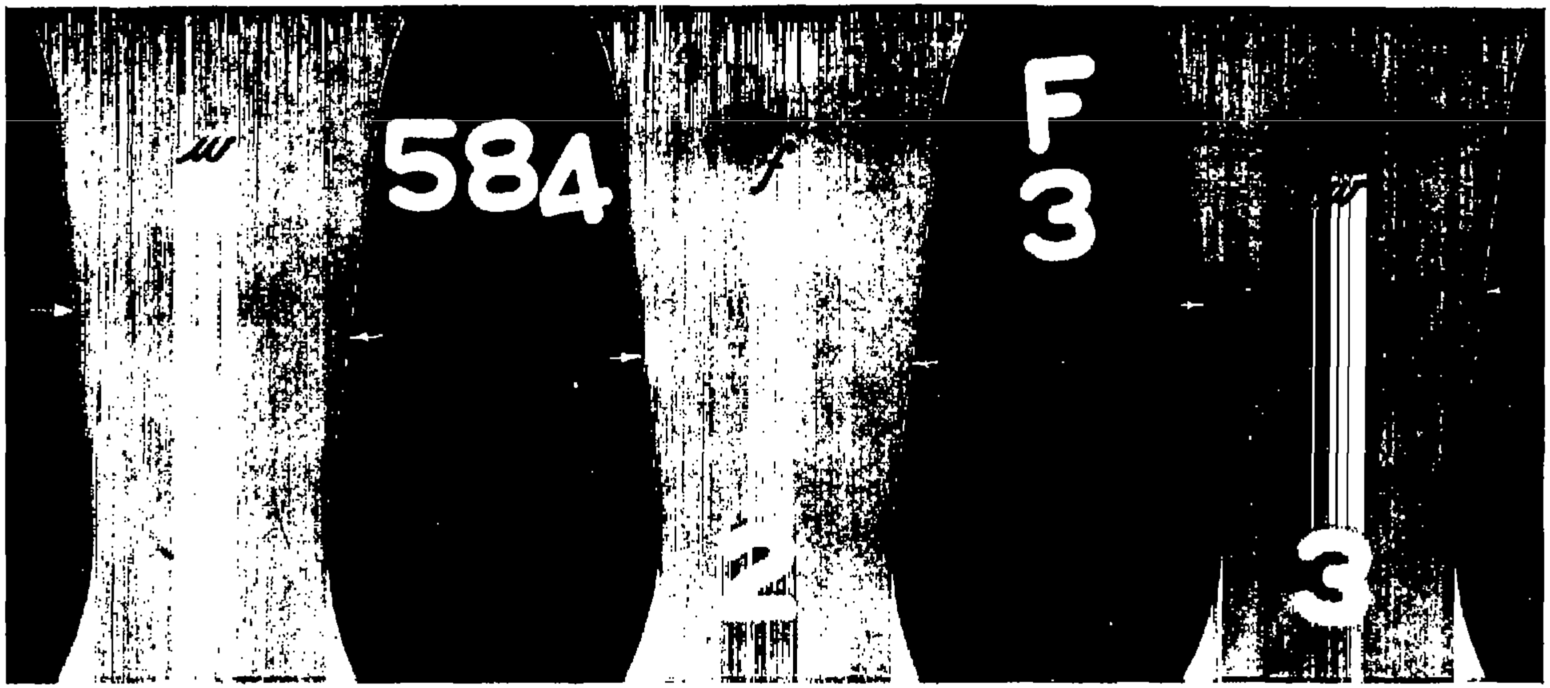
29261

Figure 20.—Krouse plate-bending machine with welded specimen in place for fatigue test.



All fatigue failures at toe of face bead;
no internal defects.

Figure 21.—Radiograph of two-bead, continuous, reinforced welds in $\frac{1}{8}$-inch SAE 4130 steel sheet (Group 1).



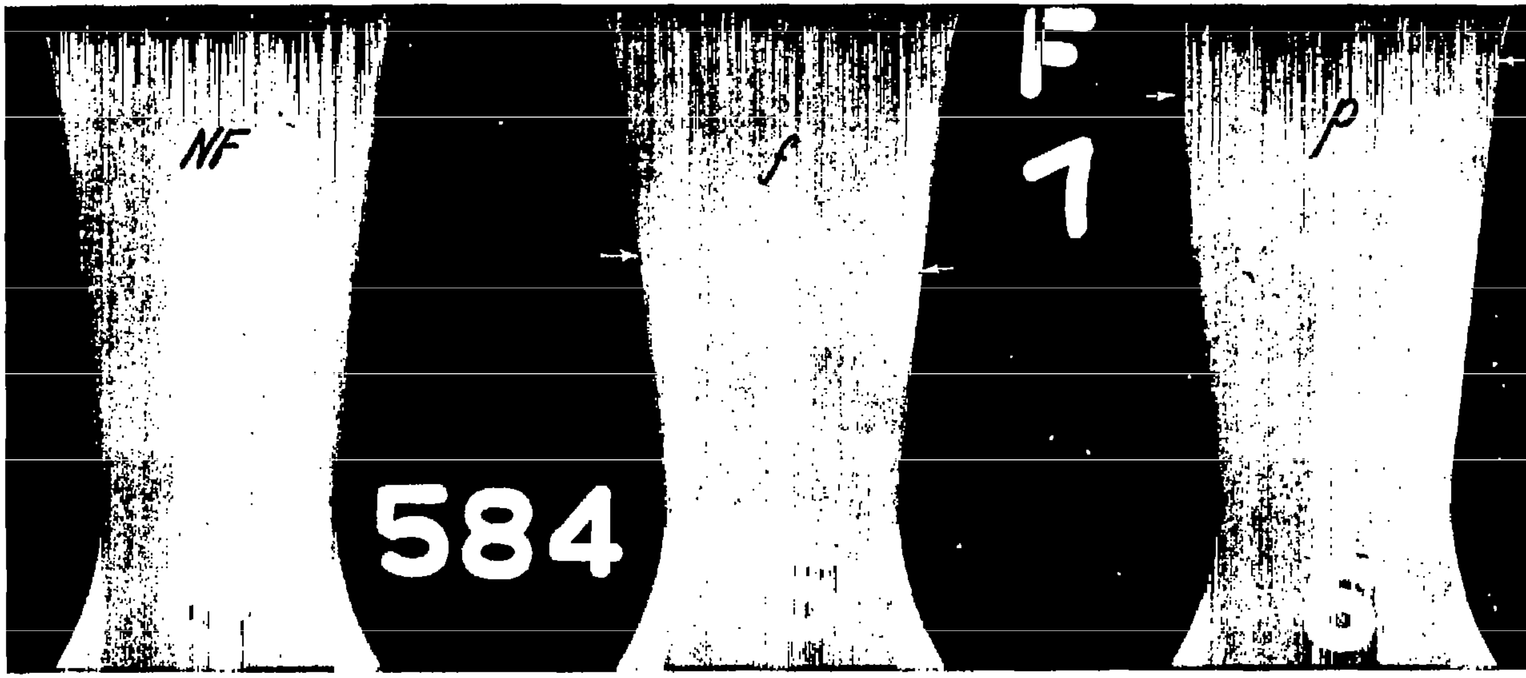
29139

Failure in weld; no internal defects.

Failure in fusion zone; no internal defects.

Failure in weld; no internal defects.

Figure 22a.—Radiograph of two-bead, continuous, flush welds in $\frac{1}{8}$-inch SAE 4130 steel sheet (Group 2).



29142

No fatigue failure;
no internal defects.

Failure in fusion zone;
no internal defects.

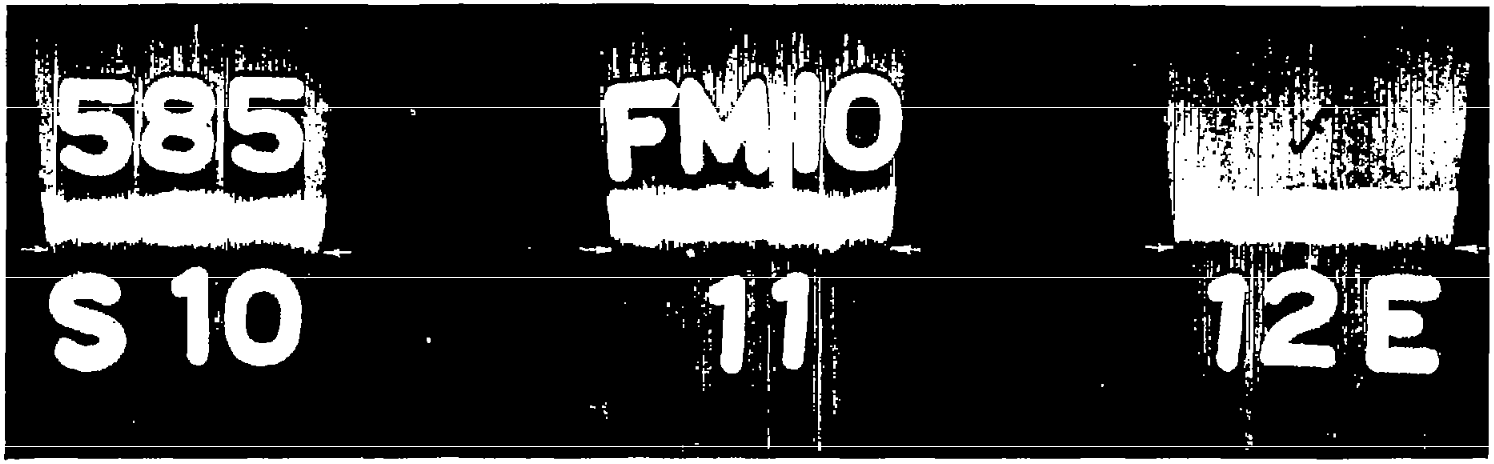
Failure in plate;
no internal defects (black spot at left is film defect).

Figure 22b.—Radiograph of two-bead, continuous, flush welds in $\frac{1}{8}$-inch SAE 4130 steel sheet (Group 2).

29134

All failures at toe of face bead;
no internal defects visible.

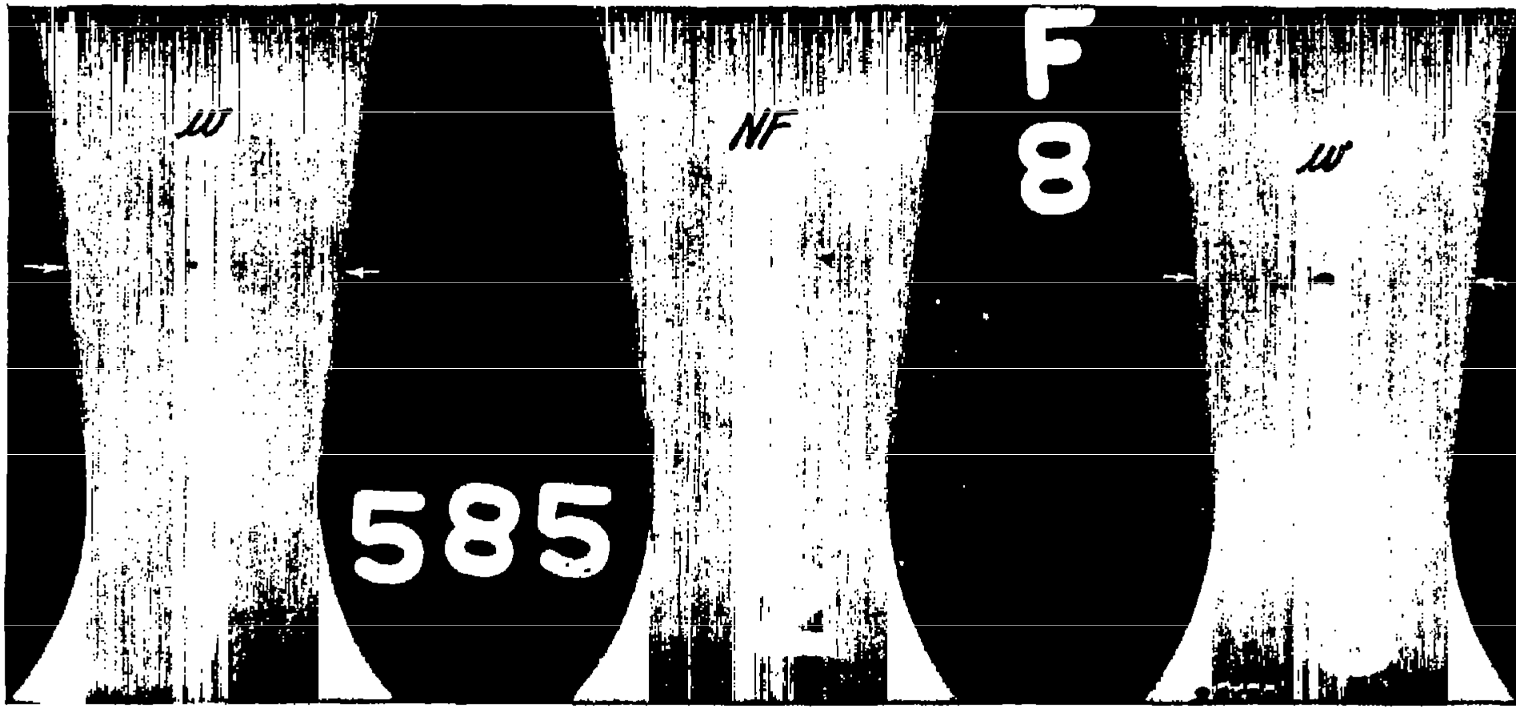
Figure 23a.—Radiograph of two-bead, interrupted, reinforced welds in $\frac{1}{8}$-inch SAE 4130 steel sheet (Group 3).



29137

All failures at toe of face bead;
minor sidewall blowholes or slag
inclusive; no crater defects visible.

Figure 23b.—Radiograph of two-bead, interrupted, reinforced welds in 1/8-inch SAE 4130 steel sheet (Group 3).



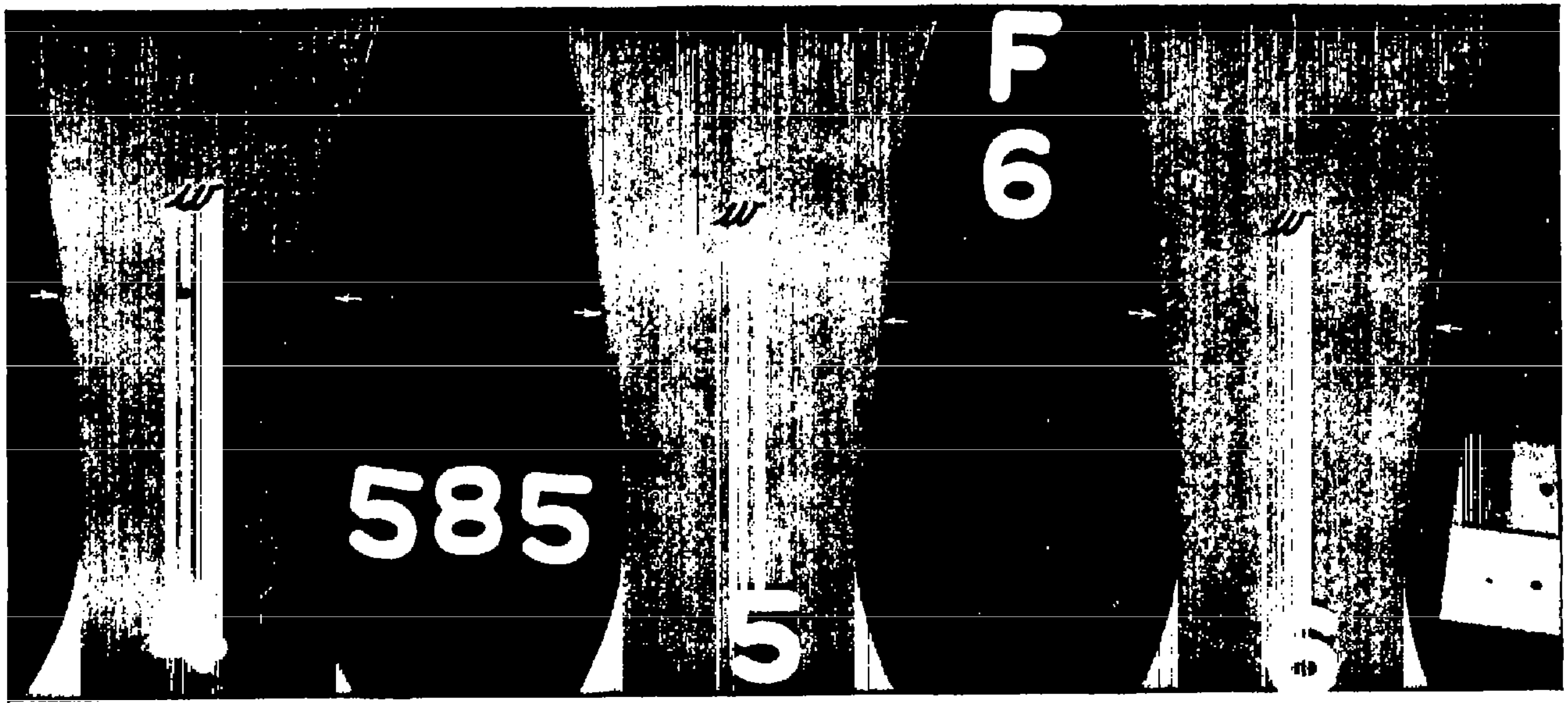
29138

Failure in center of weld; crater blowhole with transverse crack.

No fatigue failure; one sidewall pit; small crater crack (three black spots at left) are film defects).

Failure in center of weld; crater blowhole.

Figure 24a.—Radiograph of two-bead, interrupted, flush welds in 1/8-inch SAE 4130 steel sheet (Group 4).



29141

Failure in center of weld; crater blowhole.

Failure in center of weld; crater defect and crack.

Failure in center of weld; minor crater defect.

Figure 24b.—Radiograph of two-bead, interrupted, flush welds in $\frac{1}{8}$-inch SAE 4130 steel sheet (Group 4).

29135

All failures at toe of weld bead;
no root defects or lack of pene-
tration visible.

Figure 25.—Radiograph of single-bead, continuous, reinforced welds in 1/8-inch SAE 4130 steel sheet (Group 5).

29133

All failures in plate;
no root defects, except
one minor defect in No. 6.

Figure 26.—Radiograph of single-bead, continuous, flush welds in $\frac{1}{8}$-inch SAE 4130 steel sheet (Group 6).

29132

Failure at toe of weld; elongated crater blowhole and longitudinal crater crack.	Failure at toe of weld; small crater hole and transverse crater crack.	Failure at toe of weld; crater blowhole.

Figure 27.—Radiograph of single-bead, interrupted, reinforced welds in $\frac{1}{8}$-inch SAE 4130 steel sheet (Group 7).

29131

Failure in center of weld;
crater blowhole and crack;
minor root defect (X).

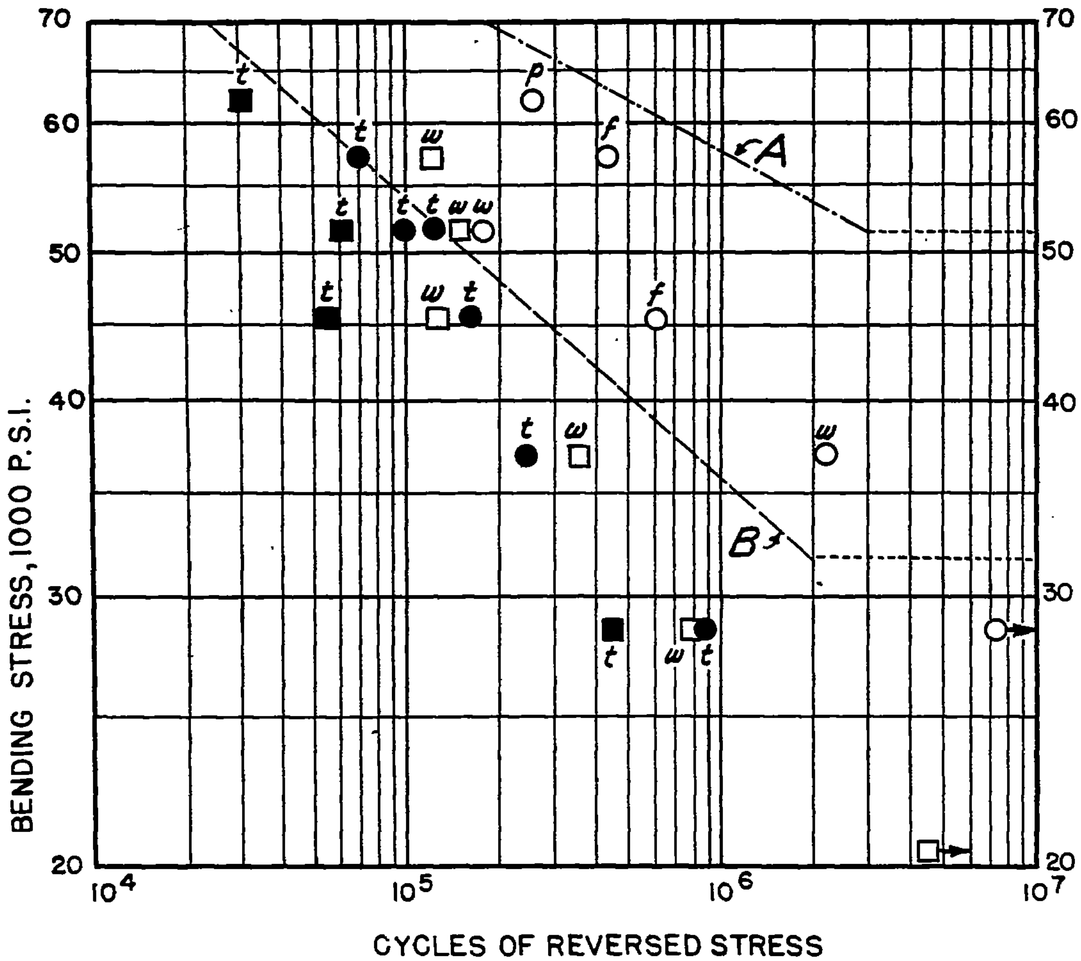
Failure in center of weld;
crater blowhole.
Crater blowholes not visible on surface.

Failure in center of weld;
crater blowhole.

Figure 28.—Radiograph of single-bead, interrupted, flush welds in 1/8-inch SAE 4130 steel sheet (Group 8).

A: REFERENCE S-N CURVE FOR UNWELDED 1/8" S.A.E. 4130 STEEL SHEET (NORMALIZED) SURFACE-GROUND BOTH SIDES TO 0.08" THICKNESS TO REMOVE ROUGHNESS AND DECARBURIZED SURFACE LAYER.

B: REFERENCE S-N CURVE FOR UNWELDED 1/8" S.A.E. 4130 STEEL SHEET (NORMALIZED) TESTED WITH AS-ROLLED SURFACE.



WELD TYPE	LOCATION OF FAILURE
○ 2-BEAD CONTINUOUS, FLUSH	p - UNAFFECTED PLATE
□ 2-BEAD INTERRUPTED, FLUSH	f - FUSION ZONE
● 2-BEAD CONTINUOUS, REINFORCED	t - TOE OF LARGE WELD BEAD.
■ 2-BEAD INTERRUPTED, REINFORCED	w - CENTER OF WELD.

FIGURE 29.-BENDING-FATIGUE TESTS OF TWO-BEAD METAL-ARC BUTT WELDS IN 1/8-INCH S.A.E. 4130 STEEL SHEET

29554

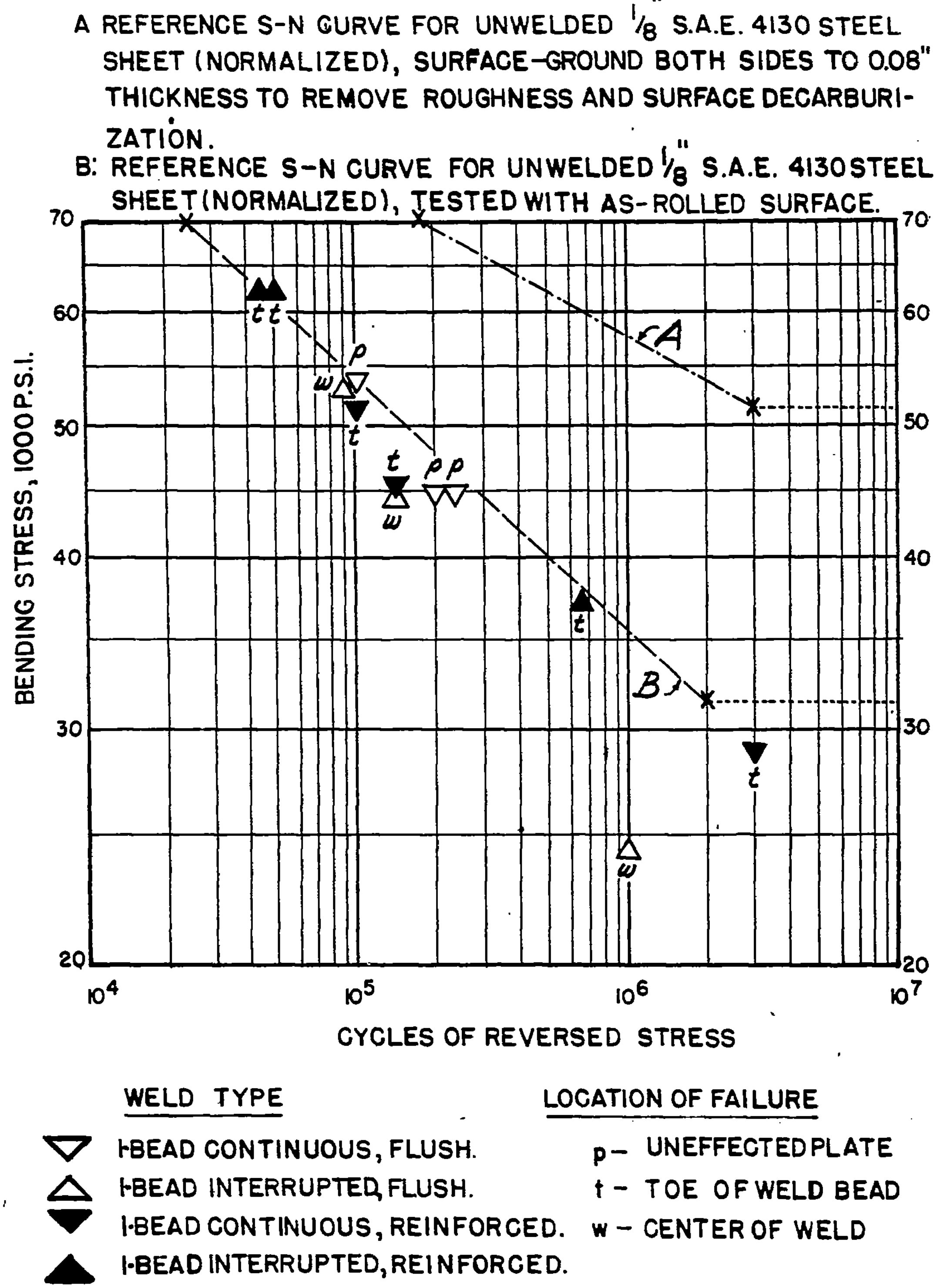
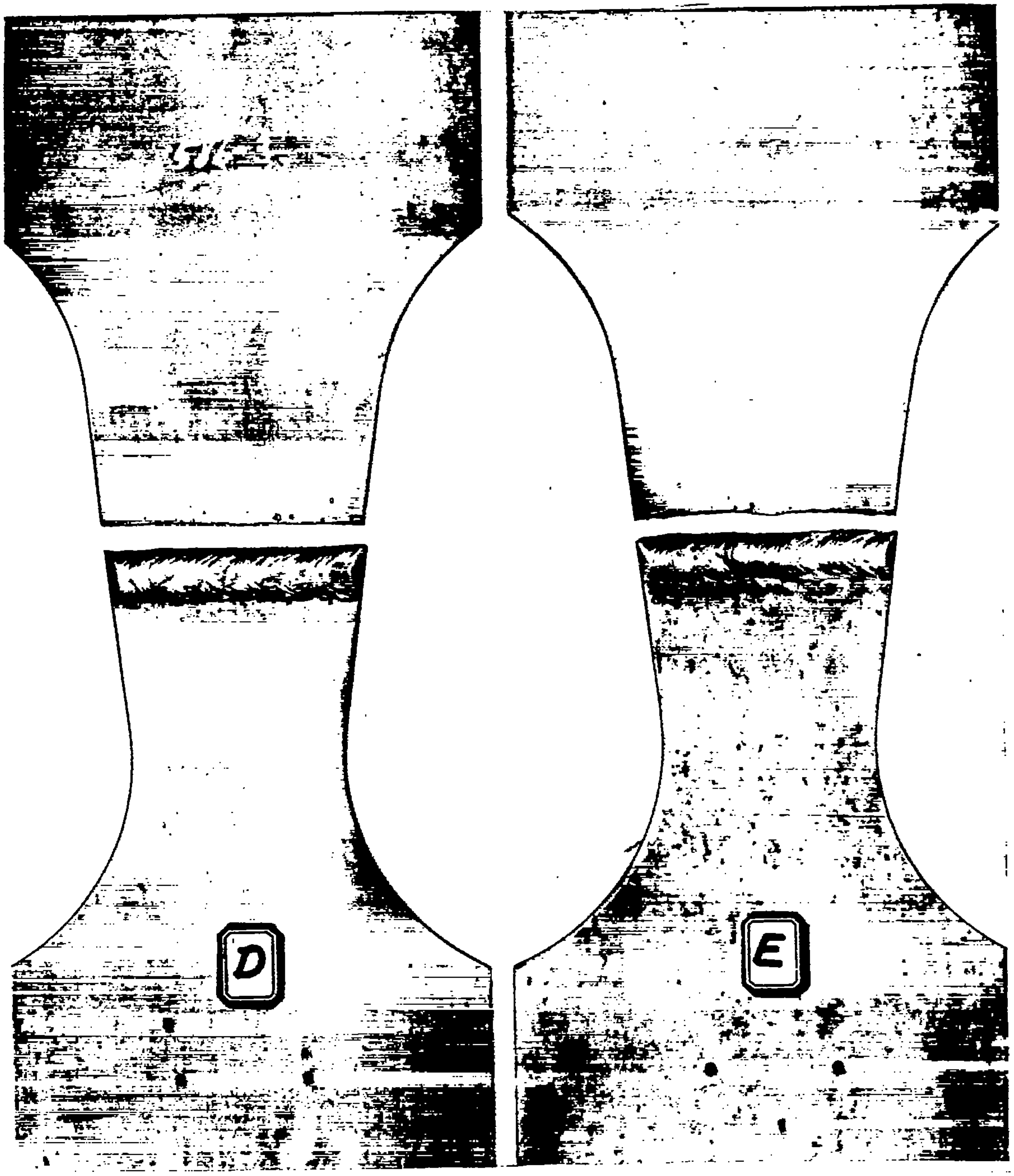


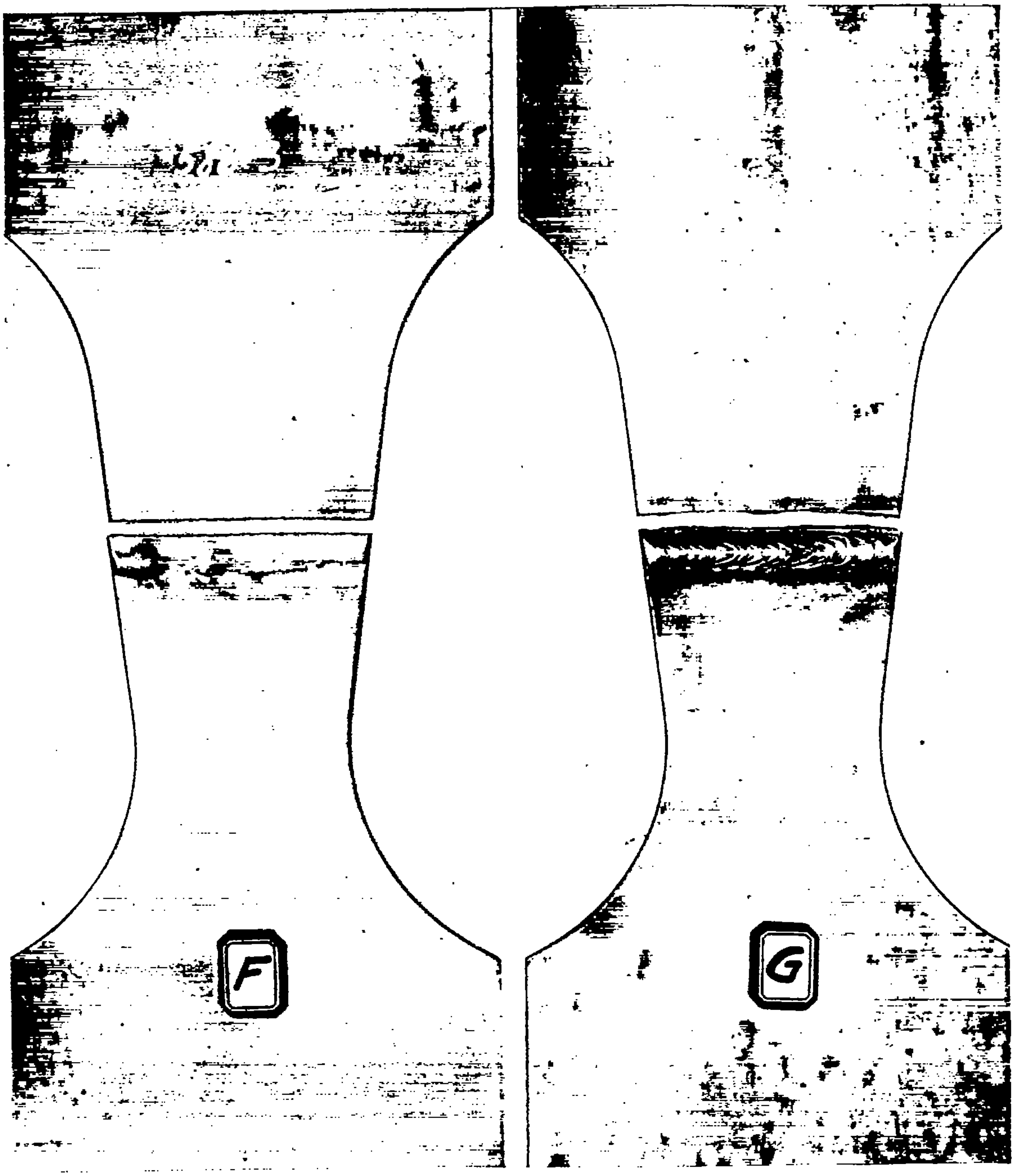
FIGURE 30 - BENDING - FATIGUE TESTS OF SINGLE-BEAD METAL-ARC BUTT WELDS IN 1/8-INCH S.A.E. 4130 STEEL SHEET.



Continuous single-bead weld (face side).

Interrupted two-bead weld (face side).

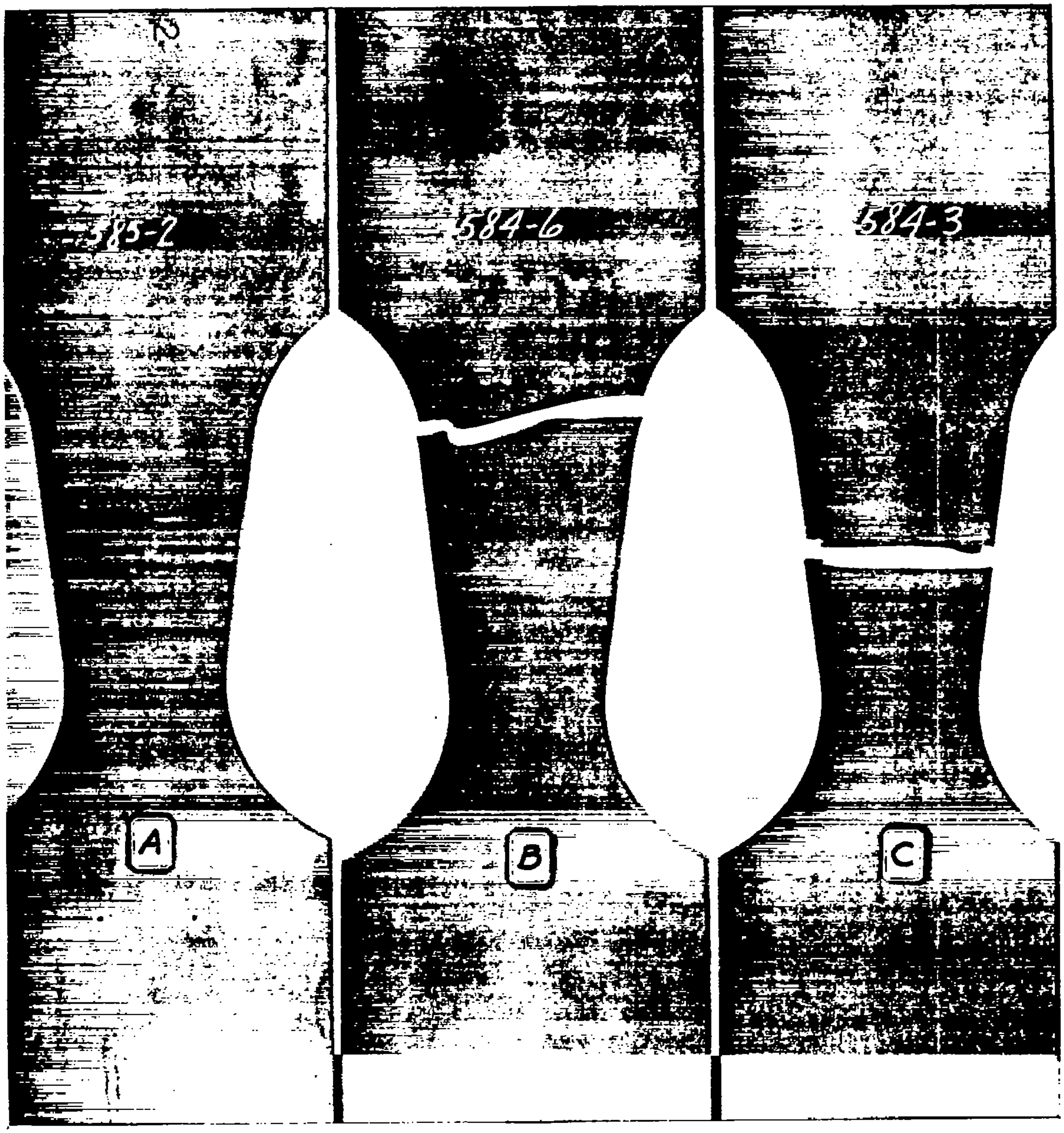
Figure 31.—Typical plate-bending fatigue fractures at toe of weld bead (face-weld views).



Continuous single-bead weld
(root side).
Failure at toe of face bead.

Interrupted two-bead weld
(root side).
Failure at toe of face bead.

Figure 32.—Typical plate-bending fatigue fractures at toe of weld bead (root-weld views).



A—Interrupted two-bead weld (no failure).
B—Continuous two-bead weld (failure in plate at change of section).
C—Continuous two-bead weld (failure in center of weld).

FIGURE 33.—Typical plate-bending fatigue fractures in welded specimens with no reinforcement

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